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INITIAL DEVELOPMENT OF A TACTICAL SYSTEM FOR DISPERSING SUPERCOOLED STRATUS

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A silver iodide pyrotechnic seeding system was selected for the development of a tactically useful approach to the dispersal of supercooled stratus. Various configurations of the pyrotechnic units were tested for nucleation effectiveness before choosing a 3/4-in diameter unit doped with a small amount of chlorine-bearing compound. The system was field tested in northern

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Michigan in February of 1977. The tests showed the system capable of producing clearings comparable to those of previous studies using dry ice as a seeding agent. Clearings were produced in clouds as warm as -8°C and as thick as 4000 feet. Targeting the clearings over a predetermined ground location was not especially difficult. While VFR flight conditions and good downward visibility were achieved, visibility on a slanted line-of-sight was poor.

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EXECUTIVE SUMMARY

The production of clearings in supercooled stratus clouds was the first demonstrated capability of weather modification technology and has been used for decades to improve visibility for aircraft operations. The methods available, however, have not been readily adaptable for use on tactical aircraft. The effort reported here represents an initial development of a system suitable for tactical use.

The physical basis for the method depends upon conversion of the supercooled water droplets in the cloud to ice crystals by introducing ice forming nuclei. Since only about one ice crystal is formed for each 1000 water droplets, the ice crystals concentrate the water into fewer (but larger) particles. This results in improved visibility in the cloud. In some cases, the ice crystals may grow large enough to develop significant fall velocities and precipitate from the cloud. Visibility is dramatically improved in such cases.

Many different methods are available to induce ice crystal growth within the cloud. A system using pyrotechnically generated silver iodide was selected because of apparent advantages for tactical use. These advantages include reliability, simplicity, minimal logistic requirements, and suitability for advanced delivery systems. In the system used, pyrotechnic grains ejected from the aircraft fall between 2000 to 6000 feet before being totally consumed in the combustion process. The smoke from the burning pyrotechnic contains silver iodide crystals which serves as ice nuclei. The pyrotechnic grains are manufactured using a mixture containing a very small amount of chlorine. Addition of the chlorine produces greater nucleation effectiveness, especially at warmer temperatures.

Field tests were conducted to determine the optimum seeding rates and patterns under varied meteorological conditions and to determine the effectiveness of the system in terms of 1) quality of the clearing produced, and 2) ability to target the clearing over a predetermined ground target. The tests were conducted in northern Michigan after an intensive site survey revealed the desirability of that area in terms of meteorological conditions, airspace availability, terrain, and logistic support. Testing began in early February and continued through early March of 1977.

Two aircraft were utilized in the tests. One performed the cloud seeding at cloud top, and the other served as an observation and command platform at higher altitude. Photographs taken from the observation aircraft served as the primary data and evaluation tool. Photogrammetric analysis of selected photographs allowed measurement of horizontal dimensions of the clearings. Ten missions were flown resulting in fifteen tests.

The major conclusions derived from the test data follow:

- It was not exceptionally difficult to target the clearings given accurate wind measurements. Even though malfunctions of the seeding aircraft autopilot hindered the cloud-level wind measurements, it was possible to successfully target nearly half of the clearings.

- The quality of the clearings (in terms of visibility) was not as good as expected, although it did appear to correspond with previous studies. In most cases, it was possible to observe the ground when looking vertically down. It was not, however, generally possible to see the ground along a slanted line-of-sight.

- The silver iodide pyrotechnic seeding system was capable of producing clearings very similar to those reported by earlier studies and appears to be a suitable choice for tactical use.

- Clearings were produced at temperatures as warm as -8°C and in clouds up to 4000 feet thick.

- Clearings up to 18 km in diameter were produced from seeding patterns measuring 4 km by 5 km.

- The assumption, common in this type of study, that ice crystals introduce a negligible obstruction to visibility is inappropriate in situations in which the visibility along a slanted line-of-sight is important.

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1. INTRODUCTION

This report documents the work performed by North American Weather Consultants (NAWC) under contract No. F19628-76-C-0306 with the Electronic Systems Division (PPR), Air Force Systems Command. The contract was awarded September 23, 1976, and the field tests were performed during the period beginning early February 1977 through early March.

The primary objectives of the work were:

1. To plan and conduct a supercooled stratus dispersal test program. The tests were designed to demonstrate the feasibility of producing clearings over pre-designated ground targets under a wide variety of meteorological and operational conditions. Particular emphasis was to be placed on targeting over a pre-selected ground location, delivery platform and tactics, and clearing size period.

2. Based on information obtained from the tests, an airborne seeding material dispenser was to be designed, fabricated, and tested. The dispenser was to be readily adaptable for use on Air Force tactical aircraft.

At the conclusion of the field tests, it was determined that insufficient data were available to allow proper design of the airborne seeding dispenser. It was therefore decided that the design, fabrication, and testing of the dispenser would be postponed until adequate data were available.

Portions of the work performed under this contract have been previously reported. The selection of a location for the field test was documented in a report entitled "Site Selection Evaluation for Conducting Supercooled Stratus Dispersal Tests" (North American Weather Consultants, 1976). The test procedures were documented in the Test Plan (Wisner et al., 1976).

2. BACKGROUND

Supercooled stratus dispersal was the first demonstrated accomplishment of modern weather modification. Extensive work has been performed on this topic and on the closely related one of fog dispersal. In this section the reader is briefly introduced to the theory of supercooled stratus dispersal, the climatology, and a review of previous work.

2.1 Theory

The empirical basis for the dispersal of supercooled fog or stratus is found in the original work of Schaefer (1948). The existence of supercooled water vapor or droplets in the atmosphere is essentially an unstable state. If ice crystals can be caused to form, they will grow at the expense of the available water since the vapor pressure over ice is less than that over water at the same temperature. As the crystals grow larger, they attain a significant fall velocity which allows them to accrete supercooled droplets as they collide. This is a faster growth mechanism than vapor deposition.

There are many more water droplets than ice crystals, typically 1000 to 1. So the ice crystals grow much larger than the water droplets were. The water is thereby concentrated in relatively few large ice crystals, rather than distributed among many small droplets. Visibility is increased dramatically as a result. The ice crystals may grow large enough to fall from the cloud. If this happens, even greater visibility results.

Several agents have been used by man to initiate this process by artificially creating ice crystals within a supercooled fog or stratus deck. Among these agents are dry ice, silver iodide, liquified propane, and compressed air. Dry ice, liquified propane, and compressed air applications operate on the principle of homogeneous nucleation. They cool a small volume of air to a very cold temperature (≈ -40°C) which allows spontaneous nucleation of ice crystals. Silver iodide applications (and potentially several other materials) operate on the principle of hetrogeneous nucleation

whereby foreign substances act as a nucleus for the formation of an ice crystal. There exist certain thresholds in terms of the upper temperature limit of effective performance of both homogeneous and hetrogeneous methods. This value for dry ice and propane spray is approximately -2°C (Weinstein and Hicks, 1975) and is approximately -4°C for silver iodide. Historically, the most frequently used agent in the United States has been dry ice particles dropped from aircraft.

Turbulence in the cloud layer provides the means of dispersing the seeding material throughout the volume to be cleared. However, after the clearing has been established, the same turbulent processes mix cloudy air in from the edges of the clearing to refill it. In situations with more intense turbulent mixing, we should expect the whole process of establishing and refilling the clearing to take place at a faster rate.

In the thinner decks, the primary effect of wind shear is to induce more intense turbulence. In thicker decks, however, an additional effect becomes important. In these cloud decks the actual difference of the velocity vectors at the top and bottom of the deck can be significant. (In thin decks, even though the rate of change of velocity with height is large, the absolute difference is relatively small.) The top of the clearing will move with some velocity relative to the bottom of the clearing. Since the useful area of the clearing is the overlapping region of the top and bottom of the clearing, the size of the useful area is reduced by the shear.

2.2 Climatology

The emphasis in this work is on the dispersal of supercooled stratus. Since supercooled stratus decks can be low enough in some areas to be classified as fog on surface observations, a brief consideration of the surface phenomenon, fog, is in order. Since fog is a surface phenomenon, there are considerably more observations of the occurrence and character of fog than there are of supercooled stratus decks.

There are three recognized types of fog, commonly referred to as ice fog, cold fog, and warm fog. Ice fogs are primarily an Arctic phenomena

which form at temperatures below approximately -30°C. They normally form near water vapor sources which are often related to man's activities. Cold fog is fog that is below freezing but is composed of supercooled water droplets. Warm fog is any fog above freezing. It is often stated that warm fog occurrences comprise some 95% of all the fog occurrences in the world.

Some areas of the earth are subject to extensive periods of fog, while others rarely experience this phenomenon. Most areas subject to fog experience a four to six month fog season. On a daily basis, fog and stratus formation often exhibits a diurnal fluctuation with a tendency for a peak occurrence near sunrise in many localities.

Less attention has been devoted to establishing climatologies of supercooled stratus occurrences presumably since the determination of the supercooled nature of the cloud is dependent upon remote measurements such as radiosondes or aircraft. Since the temperature in the lower atmosphere normally decreases 3 or 4°C per thousand feet, it is likely that supercooled stratus decks occur much more frequently than the frequency of occurrence of cold fogs would suggest. This aspect of the problem in relation to the selection of an appropriate test site will be more fully developed in Section 3.

2.3 Previous Work

Dispersal of supercooled stratus was one of the first demonstrated weather modification capabilities of man. Dr. Vincent Schaefer and his associates performed several experiments in the New England area demonstrating this capability in the latter part of 1946. The technique employed in these experiments consisted of aerial drops of crushed dry ice particles.

Research on the dispersal of supercooled fog and stratus has not been limited to government-sponsored programs in the United States. Other countries such as Russia, Norway, and France have carried out similar programs over the years. In addition, several commercial organizations (both within and outside the United States) have also been instrumental in the development

of this technology. Some of the commercial airlines in the United States have been especially active in this field.

Some of the early work conducted in the cold fog and stratus dispersion field include Project Cirrus, the Wilmington Cloud Physics Project, and the Artificial Nucleation Project. In more recent years the United States Air Force has continued this technology development. A short description of these programs follows.

2.3.1 Project Cirrus. The preliminary work of Drs. Schaefer, Langmuir, and Vonnegut at the General Electric Research Laboratory in Schenectady, New York, led to a contract with the Army Signal Corps covering "research study of cloud particles and cloud modifications" beginning February 28, 1947 (Havens, 1952). Thus began a series of laboratory and field experiments which would later become known as "Project Cirrus" (Schaefer, 1953).

Several flights were conducted in 1947 to dissipate supercooled stratus decks. These decks ranged in thickness from a few hundred to several thousand feet with base temperatures generally -4°C or colder. Seeding was accomplished by dropping sized (1/4 to 3/4 inch in diameter) dry ice particles into the top of the stratus layer. Seeding rates were on the order of one to two pounds per mile. These tests were conducted using various identifiable patterns (such as an L) and photographed. In this work the desirability of having separate seeding and observing aircraft was noted.

Flights conducted in the fall of 1948 demonstrated the feasibility of dissipating a supercooled stratus deck by seeding with dry ice. Various flight tracks such as a gamma-shaped pattern and a racetrack pattern were flown. Seeding rates were again on the order of one to two pounds of dry ice per mile. Holes in the cloud decks were produced in these experiments with ground visible for varying lengths of time up to several hours. There was some suggestion of potential overseeding with seeding rates greater than one pound of dry ice per mile.

A flight conducted in the spring of 1949 compared the effects of seeding with dry ice and silver iodide. Dry ice was dispersed at the rate of .8 pound per mile. Silver iodide crystals were produced by igniting small granules of charcoal impregnated with a one percent silver iodide solution. About 50 grams of silver iodide was dispensed along a one-mile line. No definite conclusions were reached comparing the two seeding agents partly due to the thickness of the cloud layer, which was approximately 6000 feet.

2.3.2 Wilmington Cloud Physics Project. The preliminary results of Project Cirrus provided the impetus for establishing the Wilmington Cloud Physics Project. It was established on August 19, 1947, and was a cooperative effort of the U. S. Air Force, the National Advisory Committee for Aeronautics, and the U. S. Weather Bureau (Coons et al., 1948). "The basic objective of the project was to determine in definite quantitative terms the practical limits and general utility of cloud modification processes in producing or suppressing precipitation and increasing the visibility from flying aircraft." Aerial drops of dry ice were conducted in these experiments in the Wilmington, Ohio region. Although the general goals were concerned with the possibility of either producing or suppressing precipitation, most work was oriented towards the former. Experiments were conducted on both supercooled stratiform and convective clouds. Seeding rates varied from 1 to 25 pounds of dry ice per mile. Some dissipation of clouds was noted in the experiments, although as stated before, this did not seem to be of primary interest.

2.3.3 Artificial Nucleation Project. The Artificial Nucleation Project was organized so that each of the three military services and the Weather Bureau had a separate field of weather modification research. The Army Signal Corps was assigned the responsibility of investigating the modification of supercooled stratus. The results of this work have been reported by Aufm Kampe et al. (1957).

In these tests aerial seeding flights were conducted using dry ice and silver iodide as seeding agents. A special silver iodide generator was

built for the program consisting of a gravity fed solution of 8% silver iodide being forced through a nozzle and sprayed with compressed acetylene gas. This mixture was ignited from sparks from an oil burner transformer. Dispersion rates of up to 50 grams AgI per minute were possible using this system.

Nine flights were conducted testing the effects of seeding with silver iodide. These flights were conducted 100 to 200 feet below the tops of the clouds.

The results of both the dry ice and silver iodide seeding tests were summarized in the original work (Aufm Kampe et al., 1957) and are reproduced here for reference purposes.

Dry Ice Seeding

1. It is possible to modify a subcooled cloud layer to such an extent that ground becomes visible through at least parts of it.

2. The temperature of the cloud deck should not be above -4°C, particularly if the cloud deck is thick.

3. In a thin cloud deck, 1000 to 2000 feet thick with no appreciable internal convection, an area of any size and shape can be modified so that the ground is visible through relatively large areas.

4. In thicker cloud decks holes with diameters of one to several miles may be made by seeding. However, the size and location of the holes cannot be controlled as well as in the case of thin clouds.

5. Overseeding is not as common as is generally assumed.

6. A thin cloud deck may be cleared with a seeding rate of 20 pounds dry ice per mile as well as with one pound per mile.

7. A convective cloud deck, however, may be underseeded with a seeding rate as high as 5 to 10 pounds per mile.

8. On the average, a seeded line spreads roughly one mile to either side approximately within 0.5 hour.

9. On the average, ground can be seen through some parts of the seeded area 0.5 hour after seeding.

10. In order to clear a large area, it is best to seed parallel lines three miles apart.

11. Depending on the natural lapse rate, the insolation, and the steepening of the lapse rate due to the descending ice crystals, cumulus clouds sometimes form in the modified area as a consequence of seeding.

Silver Iodide Seeding

1. Silver iodide is effective as a cloud seeding agent for the purpose of dissipating subcooled clouds; however, it is less effective than dry ice.

2. Approximately 16 grams AgI seeded over one mile correspond to a rate less than five pounds dry ice per mile. This is in agreement with data given by B. Vonnegut who seeded with AgI-impregnated charcoal.

3. The threshold temperature at which noteworthy cloud modification can be achieved appears to be approximately -10°C rather than -5°C.

4. The seeding effectiveness can probably be improved if the output of AgI crystals can be increased to 100 grams AgI per mile or more.

2.3.4 Geophysical Research Directorate. The U. S. Air Force studied the effect of seeding warm cumulus clouds under the Artificial Nucleation Project (ACN). The Geophysics Research Directorate (GRD) sponsored this work which was conducted by the University of Chicago. After the disbanding of the ACN project, the GRD and the Army Signal Corps Engineering Laboratory worked independently, then jointly, on supercooled stratus dispersal techniques. Joint operations were conducted in Germany and northern Greenland in 1956. GRD continued this work independently following the 1956 experiments in the Thule area of Greenland, northeastern Canada, and northeastern United

States, and Alaska (Downie and Silverman, 1959). These experiments were conducted using dry ice aerial drops (of 5-10 pounds per mile) and concentrated not only on the dissipation of supercooled stratus decks above the surface, but also on similar decks which were producing cold fog at the surface. Parallel seeding lines were also utilized to optimize clearings.

Some of the conclusions of this work as reported by the referenced authors are as follows:

> "Dependent upon the meteorological situation, including the amount of convergence or divergence, turbulence, cloud thickness, etc., a clearing usually results 30 to 45 minutes after seeding, with the maximum size clearing occurring on the average after about 70 minutes. Holes produced in thick cloud decks are short-lived and generally start to close in again within two hours, but clearings produced in thin clouds often persist.
>
> "The trajectory of the seeded cloud mass depends on the mean wind direction and speed at cloud level. To position a clearing over a given geographical point, then, one should know this mean wind velocity and also have some estimate of the time interval between the seeding operation and the production of the clearing. Since the time required usually varies from 30 to 45 minutes, it is necessary to seed upwind from the desired location of the final clearing a distance equal to the drift during the 30- to 45-minute 'gestation period'. As an example, for a cloud-level wind of 10 knots, the recommended location of the center of the seeded area would be about six to seven miles upwind from the desired final position of the clearing."

2.3.5 Air Force Cambridge Research Laboratories. The Air Force Cambridge Research Laboratories (AFCRL) has been active in the field of supercooled stratus and fog dispersal since the early 1960s. AFCRL conducted a comprehensive program relating various physical parameters with seeding rates, sizes of clearings, etc. using aerial dry ice methods (Vickers and Church, 1966).

A strong relationship was shown between decreasing cloud top temperature and the mean width of the strips cleared. A threshold cloud temperature of -3 to -4°C was indicated in these experiments. Seeding rates of

dry ice pellets (on the order of 1x1x1 cm) were at an optimum at about eight pounds per mile, although four pounds per mile performed satisfactorily. Rates under two pounds per mile were found to be unsatisfactory. There appeared to be no relation between cloud response and liquid water content, turbulence, and cloud thickness (up to 1500 feet). Supercooled cloud decks deeper than 1500 feet were found difficult to clear.

The attention of the AFCRL was focussed on ground based techniques for the dispersal of supercooled fog and stratus in the latter 1960s, and also on the problems of warm fog dispersal in the latter 1960s and continuing into the 1970s.

Several programs were conducted by the Air Weather Service and AFCRL on ground based supercooled fog dispersal programs. Code names such as Cold Fog and Cold Wand were attached to these projects. Various seeding agents were used including dry ice, liquid propane, and liquid carbon dioxide. Appleman and Studer (1968) have reported on these programs.

Cold Cowl was an aerial seeding program conducted by the Air Weather Service at Elmendorf Air Force Base in Alaska. Both dry ice and silver iodide were used in these tests. Multiple line seeding was used to clear holes in supercooled decks. A problem existed in these tests of properly targeting the clearing over the runway in light and variable wind cases. Silver iodide tests were considered successful (though limited in number), although a cloud temperature threshold between -5 to -10°C was suggested.

2.3.6 Foreign Programs. Other countries have been involved in the dispersal of supercooled fog and stratus over the years, notable among which are Russia, Norway, and France. The Russians have conducted experiments in the Ukraine, the Norwegians in the vicinity of Oslo, and the French at Orly Airport in Paris.

Among some of the more important indications from the work in Russia are (Polovina, 1970):

- Entire cloud must be about -4°C or colder before dispersal is possible with dry ice.

- Maximum vertical thickness of supercooled cloud capable of being dispersed by dry ice is a function of wind velocity in the cloud. If the velocity is about 20 miles per hour, the maximum depth cleared was about 2100 feet. If winds are three to ten miles per hour, then the maximum thickness should be near 3000 feet using multiple seeding lines.

- Clearing a maximum thickness of about 2000 feet with light winds is possible using a single line seeding.

- If winds are on the order of 30 miles per hour, the maximum thickness capable of being cleared would be about 1200 feet.

- The stage of cloud development is important. Cloud characteristics can change in short periods of time. Clouds in either growing or stable phases require smaller spacings in seeding lines. Higher seeding rates in growing clouds produced complete dissipation.

- Factors that seem to affect dissipation are average droplet size, water content, temperature, turbulent diffusion, and quantity of introduced nuclei per unit area.

The work of the Norwegians has indicated (Rabbe, 1969):

- Newly formed supercooled fog reacted quickly to seeding, older fog reacted slowly.

- Days when tests were conducted where temperatures were increasing (i.e., often after sunrise) often failed, best results seemed to occur in evening tests.

2.4 Summary

Research on the dissipation of supercooled stratus decks has been rather extensive. Early programs demonstrated the capability of clearing

holes in such decks using aerial releases of sized dry ice particles. Later programs established the relationship between seeding rates, size of the clearing, and some physical parameters. Discrepancies exist in the reported dependence on some parameters such as liquid water content, droplet size, etc. The following results can generally be stated for dry ice and silver iodide applications:

Dry Ice Seeding

- There is a cloud temperature threshold of -3 to -4°C above which clearings are difficult to achieve.

- Turbulence, and to a lesser extent, wind shear are important in the dissemination of the "ice seeds".

- Cloud decks with convection present require higher seeding rates than stratiform decks.

- Seeding rates of 1x1x1 cm dry ice particles have a minimum threshold of effectiveness at about two pounds per mile. Four to eight pounds per mile generally produce optimum results.

- Multiple seeding lines can be flown parallel to each other to clear larger areas.

- There are upper limits of cloud deck thickness that can be dissipated. Higher winds (which would probably indicate higher wind shears) in the cloud layer decrease the thickness that can be dissipated.

- Clouds with colder temperatures are easier to dissipate than warm ones. Colder temperatures favor larger cleared areas.

- Targeting of effect is dependent upon knowledge of the winds in the layer in combination with cloud thickness and temperature.

- Holes through which the ground is visible are created approximately 30-40 minutes following seeding.

Silver Iodide Seeding

- Silver iodide can dissipate supercooled stratus clouds, although a temperature threshold lower than that for dry ice seems to exist (between -5 and -10°C).

- Silver iodide appears to have been less effective than dry ice, although higher (greater than 50 g/mile) seeding rates may produce better results.

- Flights utilizing silver iodide have generally been conducted in the cloud to assure dispersion of the material into the cloud.

3. SITE SELECTION

3.1 Important Factors in Site Selection

Realizing that the success of the study would depend to a great extent on selection of an appropriate test area, NAWC launched an intensive effort to perform the selection immediately upon award of the contract. Several factors were carefully considered in making the selection. The most important of these are outlined in the first portion of this section. The remainder of the section describes the selection process. Since the time constraints imposed precluded a fully organized evaluation of each potential area, the selection process is best described chronologically in narrative fashion.

3.1.1 Incidence of Appropriate Weather. Since the tests required supercooled stratus clouds, it was obvious that the areas under consideration should be those that have a significant incidence of this cloud type. Data on supercooled stratus clouds are, unfortunately, rather sparse. However, potentially favorable areas can be evaluated fairly well by combining that data available with a knowledge of successful previous work in the area.

According to Guttman (1971), the greatest frequency of occurrence of supercooled stratus and low cumulus cloudiness in the northern hemisphere

during the winter season is centered in three areas shown in Figure 1. These areas are:

- Western and north-central Europe
- Northeast Asia and northwestern North America (from Korea across Japan and Kamchatka to western portions of Alaska)
- Northeastern North America from near the Great Lakes to the Davis Straits

The search for supercooled stratus clouds was not limited to low clouds or fog conditions since the range of supercooled stratus of interest extends into the middle cloud altostratus realm. The frequency of occurrence of middle clouds was also thoroughly investigated. These middle level clouds are often associated with approaching storms and frequently are found in a thickening mode.

The western and north-central European area is one of special interest since a large portion of the area is covered by supercooled clouds a significant portion of the time. This area would offer the opportunity for a large sample of cases under a variety of weather conditions as desired. The Air Force has conducted successful cold fog clearing operations in this area (using a liquid propane ground system since 1970-71) at Hahn Air Base in Germany (Chary and Lininger, 1975).

The area which covers portions of eastern Asia is mostly over the ocean or over portions of Russia. Practical aspects preclude consideration of this area; however, the northwestern portion of North America (which is within this high frequency of occurrence area) did appear to offer some potential test sites. In particular, the southern and southeastern portions of mainland Alaska appear promising. Project Cold Cowl (Appleman, 1968) demonstrated the effectiveness of using dry ice seeding for the dissipation of cold fog at Elmendorf Air Force Base near Anchorage during 1967-68.

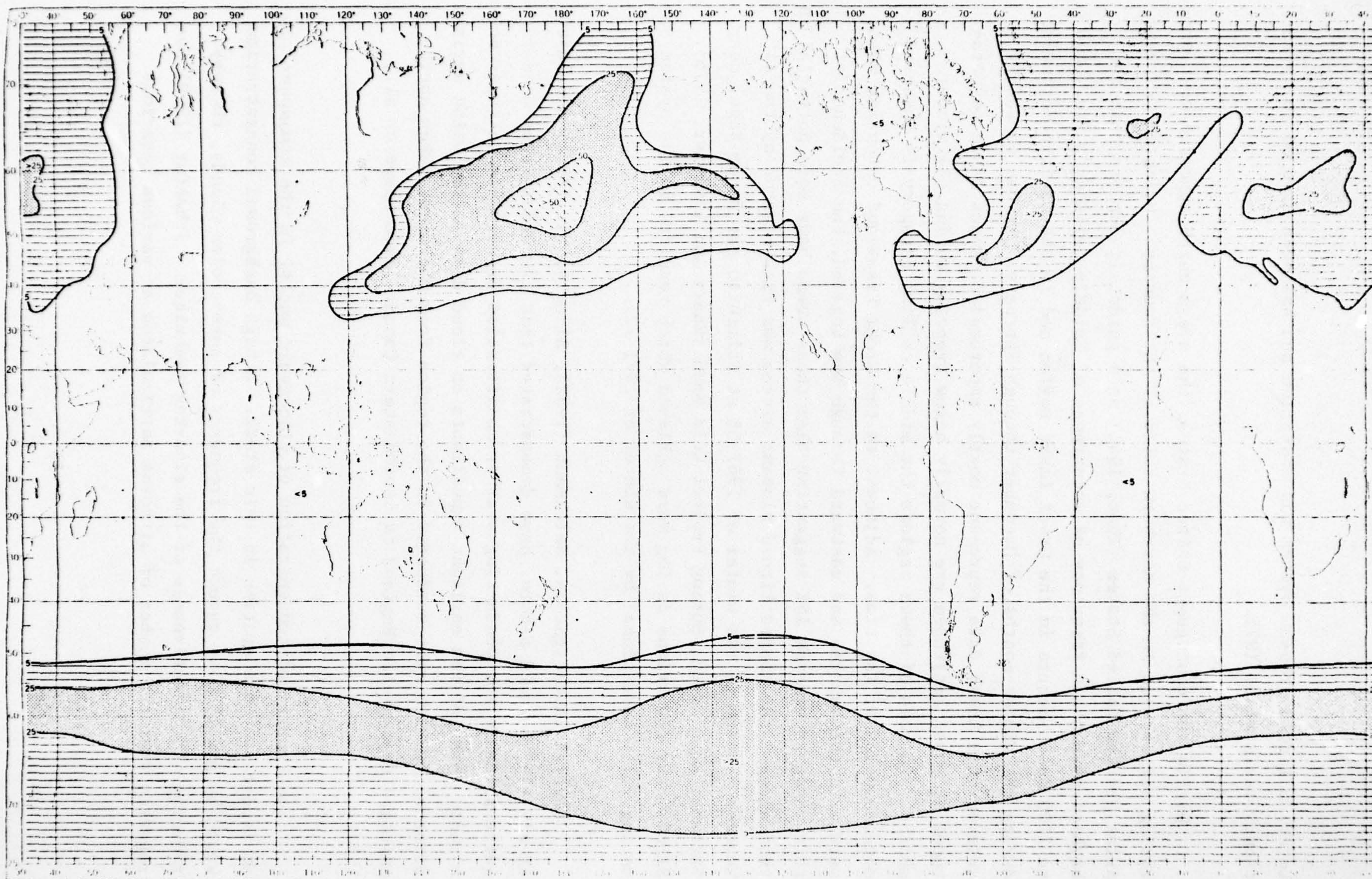

Fig. 1 Dec., Jan., Feb. percentage frequency of occurrence of supercooled stratus and low cumulus (after Guttman).

Later, a liquid propane system was installed and has been used on an operational basis since 1973.

Within the contiguous United States, the areas which appeared most promising are located in the northern third of the country. Using the Airways Atlas for the United States (Thom, 1941) as a guide, it appears that the highest percentage frequency of occurrence of "middle ceilings"; i.e., 600 to 2000 feet, occurs in the Great Lakes region and in the Pacific Northwest during the winter months of December through February. It can be safely assumed that these data represent mostly supercooled clouds since temperatures at those latitudes are normally below freezing during the winter months. In both of these regions the middle ceiling category is observed more than 25% of the time. Adjacent to the Great Lakes and extending westward into the Dakotas and eastward through New England, the incidence of this category exceeds 15% suggesting that these areas have some potential as test sites. The vented liquid propane system was first tested by the Air Weather Service in the winter of 1967-68 at Fairchild Air Force Base, near Spokane, Washington, during Project Cold Wand (Chary and Lininger, 1975). Significant reductions in fog were achieved which resulted in the system becoming fully operational by the winter of 1971-72.

Several investigators, Weickmann (1972), Allee et al. (1972) and Justio et al. (1970) among others, have demonstrated that the Great Lakes area is quite suitable for conducting weather modification experiments on supercooled clouds. Some of the earliest experiments on cloud dissipation using aerial drops of dry ice were conducted in the region from the Great Lakes northeastward through New England to southeastern Canada (Aufm Kampe et al., 1957).

The background concentration of glacogenic nuclei in the atmosphere is an important consideration in this study. A high background concentration would be expected to reduce the frequency of supercooled clouds, thereby reducing the effectiveness of the clearing technique. Schaefer (1969) has reported that the number of airborne particulates at various locations

throughout the United States during the past decade has increased by an order of magnitude. He has observed that supercooled clouds over and downwind of cities in the northern United States during the winter months are being overseeded by this outpouring of industrial pollution. Hogan (1968) has demonstrated that a similar zone of air pollutants is being emitted from the industrial areas of Europe and the British Isles as well. Warner (1968) has reported that in the Hawaiian Islands large clouds form over sugar cane fields when they are burned, but these clouds do not precipitate even though smaller ones nearby produce showers. This suggests that ice nuclei, if present, are being deactivated by the high concentration of smoke particles and gases flowing into the base of the clouds. It would appear that most occupied areas of the world are being influenced by man's industrial activity, and it may be that no test area can be found that is free from this influence. Even if one were to be found, it should probably be rejected as a test site since it would be unrepresentative of the atmosphere most likely to be encountered in actual operations. Certainly, this would be so if operations are anticipated on supercooled stratus around the industrialized centers of Europe, Asia, or the Americas.

3.1.2 Terrain Characteristics. Terrain can have a considerable influence upon the weather even at remote distances; i.e., Foehn effects or gravity waves downwind from a mountain range. Locally, of course, terrain can have a pronounced effect on the occurrence of fog or low clouds. It was considered desirable to eliminate these influences as much as possible, so that an objective evaluation of the results of the tests could be made. Another factor considered was the effect of terrain (primarily higher mountains) on the safety of operations. The aircraft operations were generally conducted under VFR-on-top conditions, but this did not preclude the possibility of cloudiness obscuring nearby mountain peaks at heights above the operating altitude of the aircraft. There is little question that flat terrain is most desirable, and this was a strong consideration in deciding on a test area.

3.1.3 Licensing Laws. Approximately 30 states have passed legislation regulating weather modification activities. In the international arena, attitudes toward weather modification vary greatly from country to country. The licensing process is often time consuming and uncertain. The timely deployment of this project required that the study area be free of licensing requirements or subject to essentially nonrestrictive legislation.

3.1.4 Logistics. The primary logistic considerations centered around the project aircraft. These included:

- Availability of adequate service and maintenance facilities.
- Potential problems in coordination with air traffic controllers; e.g., heavy air traffic or inadequate air navigation facilities.
- Availability of adequate alternate airports.

In addition, there needed to be suitable accomodations for the field crew. The availability of local and area weather information was also considered to be quite desirable. In particular, it was felt that the area should be within reasonable proximity to winds aloft data from a local National Weather Service station.

3.2 Selection

3.2.1 The Selection Process. The approach that was adopted was to first consider a wide range of potential sites based on the incidence of the appropriate cloud type and weather. Different climatological and geographical conditions prevail in North America than in Europe, with the result that weather situations similar to those in Europe are not common in the United States. For this reason the central European region was considered as a test site, but was rejected as being economically not feasible. However, stratus and stratocumulus clouds are found in significant amounts in many regions of the North American continent. It was determined that sufficient supercooled stratiform cloud was available for study in several

sections of the North American continent north of about 40° latitude. Specifically, those areas which exhibit considerable supercooled stratiform cloudiness in the winter months are:

1) The coast areas of the northeastern United States, 2) the State of New York, 3) the States of Ohio, Indiana, and Illinois, 4) that portion of the United States and Canada surrounding the Great Lakes, 5) the State of Alaska, 6) the coastal areas of eastern Canada, and 7) the State of Washington.

It was decided that the site selection would come from one or more of the areas listed above employing a process-of-elimination approach based on the availability of airspace, logistical constraints, and the effects of terrain in influencing the cloud and weather patterns. Since the time frame from site selection to field testing was very short, it was felt that those areas which required public hearings, licenses or permits should also necessarily be eliminated from consideration. This immediately eliminated the states of Illinois, Wisconsin, and Washington.

It was quickly determined that the logistical problems inherent in operating the field test in Canada were considerable, and utilization of Canadian airspace should probably not be considered feasible within the time frame available. Therefore, area 6 above and those Canadian regions of area 4 were eliminated from consideration.

After this initial elimination the following areas remained:

1) New England, 2) New York, 3) Northwestern Ohio and Northern Indiana, 4) Michigan, and 5) Alaska.

Connecticut and Massachusetts were eliminated next because coordination with the regional Federal Aviation Air Traffic Controllers suggested that airspace in these regions would be difficult to obtain. Northern New Hampshire and Vermont were not included in the survey due to the mountainous character of the area. The potential operating areas in the State of New

York were limited to that portion south of Lake Ontario for much the same reasons. Upper New York state was considered too mountainous because of the Adirondack Mountains. Southeastern New York contains the Catskill Mountains as well as congested airspace near New York City.

After these preliminary eliminations the major factors that were considered in completing the site survey were the climatology of the areas and the availability of airspace to conduct the tests.

3.2.2 Area Climatology. It was felt that it would not be possible to develop a complete climatology for these areas in the time available but a limited study for the months January through March was made for a five year period from 1971-75. Surface hourly weather reports for several airports within these areas were examined utilizing a subjective system whereby each day was examined on the basis of specific weather parameters. Each day was classified as operable, marginal, or not operable because of precipitation.

On the basis of the climatological study, Ohio and Indiana were eliminated due to a large percentage of warm stratus (defined as minimum in cloud temperature -3°C or warmer). Alaska (Anchorage area) was eliminated because the study suggested that while the area had suitable conditions it was also subject to prolonged periods of clear weather.

3.2.3 Summary and Recommendations. After considering all the factors, it was evident that meteorologically the three areas of Michigan, New York, and New England were clearly the best. Operations might reasonably be expected to be conducted on about two-thirds of the February days in Michigan and on about one-half of the days in New York or New England. Air traffic considerations indicated that the New York area should be dropped and suggested that the potential test area sites in either Michigan or New England be located north of the congested areas. In Michigan, it appeared that this requirement could be met by operating north of a line from about Ludington to Standish. In New England, to satisfy the requirement, the southern limits of the test area should be north of a line from Portsmouth to Manchester,

New Hampshire, with the test area extending northward into central Maine. This test area was limited to the north and west by the mountainous terrain of northern New Hampshire and northwestern Maine and to the east by the Atlantic Ocean. These limitations created a relatively long but narrow test area which could have proven to be a problem at times when the winds aloft were normal to the long axis. In Michigan, the major adverse meteorological condition that could have affected the results was the effect of the Great Lakes. The lakes have the effect of supplying additional moisture and instability to the clouds causing thicker and persistent cloud and local snow showers. This effect is greatest near the shoreline and diminishes inland generally being confined to an area 30-50 miles downwind from the lakes. This effect is at its maximum in November and December, and drops to a minimum in January and February. By confining operations to the central and eastern portions of the state, it was felt that the lake effect could be minimized.

Considering all of the factors, NAWC recommended that the test site area should be located in the state of Michigan. It was felt that overall this region offered somewhat more potential than the New England area. NAWC initially suggested that several ground targets be identified in central Michigan with operations conducted out of the airport at Saginaw. When it became evident that operations around the Saginaw area might be restricted, it was recommended that the operations center be located at Traverse City with ground targets selected in the northern portion of lower Michigan. This recommendation was accepted by the Air Force. Subsequent successful experience is testimony to the choice of both the area and the base of operations.

4. SEEDING SYSTEM

The results of past work indicate that a useful operational stratus dispersal system can be developed in a short period of time if the effort is restricted to seeding and delivery techniques within the present state of the art. Significant tactical advantages could be introduced into the system by extending the state of the art, especially in the area of seeding material delivery systems. However, delaying the deployment of a useful

capability for the potentially protracted development of more advanced delivery systems would be unwise. NAWC's approach has been to develop an operational system readily adaptable for use by Air Force tactical aircraft. The system would be immediate useful but would be designed to take full advantage of future advances in the technology.

4.1 Criteria

Several important factors must be considered in developing a system for airborne tactical applications:

- Standoff Range. This should be as large as possible. If the area to be cleared of stratus is heavily defended, it should obviously be avoided by as great a distance as possible.

- Exposure Time. In a tactical situation the longer the seeding aircraft remains near the target, the greater are its chances of sustaining injury. This exposure must be kept as short as possible.

- Altitude Freedom. The aircraft's vulnerability can be determined to a large degree by the altitude at which it flies. If the seeding system is flexible with respect to altitude, the seeding aircraft can choose an altitude which takes advantage of refraction phenomena such as "radar holes".

- Reliability. Reliability must be designed into the basic structure of the system. A system which is capable of wondrous feats, but cannot be depended on, is of little tactical use.

- Operational Simplicity. This is almost a corollary of reliability. Under the stress of the tactical environment, even very competent pilots and crews cannot be expected to successfully implement a complicated procedure.

- Logistics. The system should not be logistically demanding. Features requiring special handling or storage precautions should be avoided.

• Versatility. The system should be usable on several different types of aircraft and should be capable of treating a variety of meteorological situations.

• Economy. The design should arrive at the most economical system consistent with the objectives.

Standoff range, exposure time, and altitude freedom stand to benefit most from the development of more advanced delivery methods. The remaining factors mentioned above would probably suffer in varying degrees. If the seeding material could be delivered to the appropriate area by an air-launched missile, the safety of the seeding aircraft could be improved. Another method might be to use a "cluster bomb". This could be dropped from any altitude. An explosive charge activated by a pressure sensitive device at the proper altitude could then disperse the seeding material in the desired pattern. "One pass" techniques could also be developed in which the seeding aircraft is required to fly over the seeding area at cloud top on only one pass. This requires the ability to "shoot" the seeding material a few miles to either side of the path of the aircraft. Successful development of any of these techniques would require a significant effort which is unwarranted at this stage.

The seeding technique commonly used requires the aircraft to fly a multiple-leg pattern at, or possibly somewhat below, cloud top. It is important to realize that this approach does not expose the aircraft as much as one might suspect. The time required to seed an area of 25 $(\text{n mi})^2$ would be only about five minutes. Since the seeded area would be displaced from the area of desired clearing by about 45 minutes of cloud movement, moderate wind conditions would afford reasonable standoff ranges. For example, the standoff range in a 20-kt wind would be 15 n mi. Stratus layers at any level much above the ground may frequently be associated with winds of 20-kts or greater (see, for example, Vickers and Church, 1966) depending upon the climatology of the area. Situations with light winds would be more dangerous to treat with this technique. These situations would generally be associated with fog or very low stratus decks.

4.2 Critique of Available Systems

Ejectable Pyrotechnics. After careful consideration of the multitude of glacogenic nucleation systems available, a silver iodide ejectable pyrotechnic system was selected. Most of the available seeding materials would perform quite adequately the task of clearing supercooled stratus clouds. So the choice of the system best suited for this application was determined primarily by superiority with respect to:

- Reliability
- Simplicity of operation
- Minimal maintenance requirements
- Minimal logistical requirements
- Suitability for use by advance delivery systems

Systems of this type consist of ejectable pyrotechnic seeding cartridges and a dispensing rack. The seeding cartridges contain an ignition mixture, an ejection mixture, and a seeding mixture. The pyrotechnic grain containing these mixtures is pressed into a metal shell hollow at one end, similar to a signal flare cartridge. An electrical igniter is installed, and the cartridge is sealed against moisture. The dispensing rack is mounted on the desired aircraft and loaded with several dozen seeding cartridges. The units are ejected in flight as desired by the pilot.

The cartridges are very durable and require minimal special treatment from a logistical standpoint. They are generally considered Class C explosives, which puts them in the same category as common road flares. Accidental or spontaneous ignition is extremely unlikely. Storage life varies from one mixture to another, but is generally several years.

The dispensing rack is similarly undemanding. It requires no special storage or handling and contains no complex components or operating systems. Its function is simply to hold the cartridges in position and apply the ignition voltage to the correct cartridge at the appropriate time. The

electrical circuitry required for proper ignition control is quite simple and can be designed to be very reliable. Preflight preparation of the system consists of 1) mounting the rack on the aircraft, 2) checking for proper operation of the ignition circuitry, and 3) loading the desired type of seeding cartridge. The Naval Weapons Center has developed a system of this type (SUU-53/A) which is approved for use on tactical aircraft.

Stormfury System. The Naval Weapons Center has developed a seeding system for Project Stormfury which would have some advantages for this purpose. The system uses a small diameter (3/8 inch) pyrotechnic grain. The grain is encased in a frangible phenolic tube with an aluminum cap on one end which houses a percussion igniter. The pyrotechnic units are loaded in a magazine, then released one at a time (cap down) into a nearly vertical fall tube. At the end of the tube is a firing pin which activates the percussion igniter as the unit exits the aircraft. The unit burns at the cap end as it falls, separating the cap from the grain.

The primary advantages of this system are a small unit charge and an ability for rapid fire releases. Together these allow significantly more variation in semicontinuous seeding rates (grams per mile) than other systems using discrete seeding units. The small diameter of the grain also allows more effective production of nuclei, so less silver iodide is required. The main disadvantage of this system is the aluminum cap (3 grams) which free-falls to the ground and could do significant damage on impact. The weight of the cap could be reduced to about 1.5 grams if plastic were used instead of aluminum. Whether this would reduce the risk to acceptable levels, however, is questionable. Another disadvantage is the relatively complex mechanism of the dispenser.

Dry Ice. The vast majority of past stratus clearing efforts have used dry ice (solid CO_2). Although this material is quite desirable in civilian applications, it is impractical for military use. Since the dry ice sublimates at high rates unless refrigerated to -78.5°C or colder, it cannot be stored for more than a day under normal conditions. Even though storage

life can be extended to several days if an insulated container is used, a source of the material would have to be readily available at all times. This is impractical in the tactical environment.

Liquid CO_2. The most practical way to handle CO_2 in field use would be in its liquid form. It is commercially available in high pressure containers. Outside of the normal precautions for handling high pressure containers, the logistical requirements for such a system would not be too demanding. The main concerns would be that the containers never be exposed to heat in excess of 125°C, since they will then reach a "liquid-filled" condition and experience extremely high pressure with probable rupture.

Vickers and Church (1966) reported on the use of a seeding device (Cloud Buster) which converted the liquid CO_2 to solid pellets at 33% efficiency during the seeding operation. The device had several moving parts, and difficulty in maintaining reliable operation was indicated in some of the earlier reports. Even with additional engineering development, it is felt that such a system would pose significant maintenance and reliability problems.

Acetone Burners. Combustion of acetone solutions of silver iodide has been a standard method of generating ice nuclei for many years. Systems of this type are typically undesirable for tactical uses. They require mixing (probably in the field) of the seeding chemicals into the acetone. If the solution is mixed improperly or stored improperly, its nucleating effectiveness can be significantly reduced. The liquid is volatile, toxic and flammable, and it is unpleasant to work with under adverse conditions. Clogging of the liquid lines and unreliable ignition have been chronic problems with these units. Required maintenance and preflight servicing have generally been quite high.

The Naval Weapons Center, China Lake, has developed a system which seems to have overcome several of the chronic problems of this approach. The dispenser, designated as "Dispenser, Glacogenic Nuclei SUU-56/A", is

approved for use on high speed tactical aircraft. The acetone solution is premixed and stored in 15-gallon stainless steel drums. Storage life is reported to be on the order of one year if the solution is filtered before it is placed in the drum. For additional information, the reader is referred to the technical manual (Naval Weapons Center, 1976).

It was planned to include this unit in the field tests as a secondary system. However, problems were encountered in obtaining FAA approval to mount the dispenser on the seeding aircraft.

Pyrotechnic Flares. Pyrotechnic flares which burn in place on the aircraft would be another possible approach. A drawback to this and the acetone burner is the lack of immediate distribution throughout the vertical extent of the cloud which is realized with the ejectable pyrotechnics or the dry ice methods. Another consideration is the warning from our consultant, Mr. Irwin Koff, that such systems are very difficult to successfully certify for use on military aircraft.

Other Seeding Agents. Several nucleating agents other than silver iodide are available. Many of these can be generated with pyrotechnic devices which would be compatible with the suggested approach. Formulations using lead iodate are presently receiving some degree of interest for their high nucleating efficiencies at warm temperatures. Environmental concerns about the potentially harmful effects of lead in the atmosphere and water supplies has essentially precluded the use of lead iodide in any large scale field programs in the United States. It is, however, commonly used in hail suppression programs in the Soviet Union. Silver iodide, on the other hand, has been extensively utilized in weather modification programs (especially precipitation enhancement and hail suppression programs) since the discovery of its ice nucleating properties by Dr. Vonnegut.

Several organic materials also produce effective artificial ice nuclei. Two of the more common agents are 1,5 - dihydroxy-napthalene and metaldehyde. These were eliminated from consideration because it was felt there was insufficient experience with their use.

Propane and compressed air can be released through nozzles to produce ice crystals via homogeneous nucleation. Although these techniques have been used successfully for ground-based stratus clearing, their use in airborne applications was felt to be inferior to the ejectable silver iodide cartridges. They are also not amenable to the development of advanced delivery systems.

<u>Discussion</u>. The potential advantages of silver iodide pyrotechnics in tactical applications suggest that this agent should receive primary consideration. Ease of storage, handling, and delivery are all strong arguments for this emphasis. Ejectable units,in particular,offer considerable flexibility in future dispenser designs. Multi-unit ejectables could conceivably be mounted in a missile or cluster bomb configuration which would allow remote delivery of the seeding material. This, of course, would provide a significant tactical advantage. Another advantage would be the ease of controlling the rate of seeding material output. Such changes can be made by selectively firing units of higher output or by adjusting the interval between firing.

The primary disadvantages of silver iodide pyrotechnics compared to dry ice appears to be 1) lower effective temperature threshold, 2) potentially higher unit cost per mile of seeding. There are several gaps in our knowledge of the potential effectiveness of silver iodide in dispersing supercooled stratus due to the preponderance of previous experimentation being conducted with dry ice. Seeding rates, methods of generation, and methods of delivery of silver iodide have not been fully documented in these studies. As has been shown in other applications, the method of generation can have a strong influence on the effectiveness of the material.

4.3 NEI Seeding System

The pyrotechnic system selected for use was developed by Nuclei Engineering Inc. (NEI) of Louisville, Colorado. The pyrotechnic seeding units are approximately 3/4 inch in diameter and five inches long. Three different grain sizes were used. The length of the pyrotechnic grains was adjusted

to produce 10-, 20-, and 30-gram silver iodide outputs. The pyrotechnic material is a chlorine-doped version of the standard NWC TB-1 formulation. The approximate fall characteristics are listed below:

AgI Output	Burn Time	Fall Distance
10 g	24 sec	2000 ft
20 g	44 sec	4000 ft
30 g	64 sec	6000 ft

The rack to carry these seeding units on the belly of the seeding aircraft was obtained from AeroSystems, Inc. of Boulder, Colorado. It is shown in Figure 2 along with the seeding units.

CSU Tests. It was felt that three aspects of the seeding system should be confirmed prior to final selection. These were:

1. Potential differences between dry mix and acetone mix methods of manufacture.

2. Nuclei production characteristics of the chlorine-doped versus the standard TB-1 formulation.

3. Nuclei production characteristics of the small diameter versus the standard diameter.

A series of tests were performed at the Colorado State University Cloud Simulation and Aerosol Laboratory to investigate these points. Time constraints limited the number of tests and thereby the conclusiveness of the results. However, the appropriateness of the selected system seemed to be confirmed.

Acetone vs. Dry. Figure 3 shows the results of tests using the selected grain (dry mix) and grains made using the acetone mix process. No significant difference is apparent between the two processes. It was therefore decided to use the dry mix process because of ease of production.

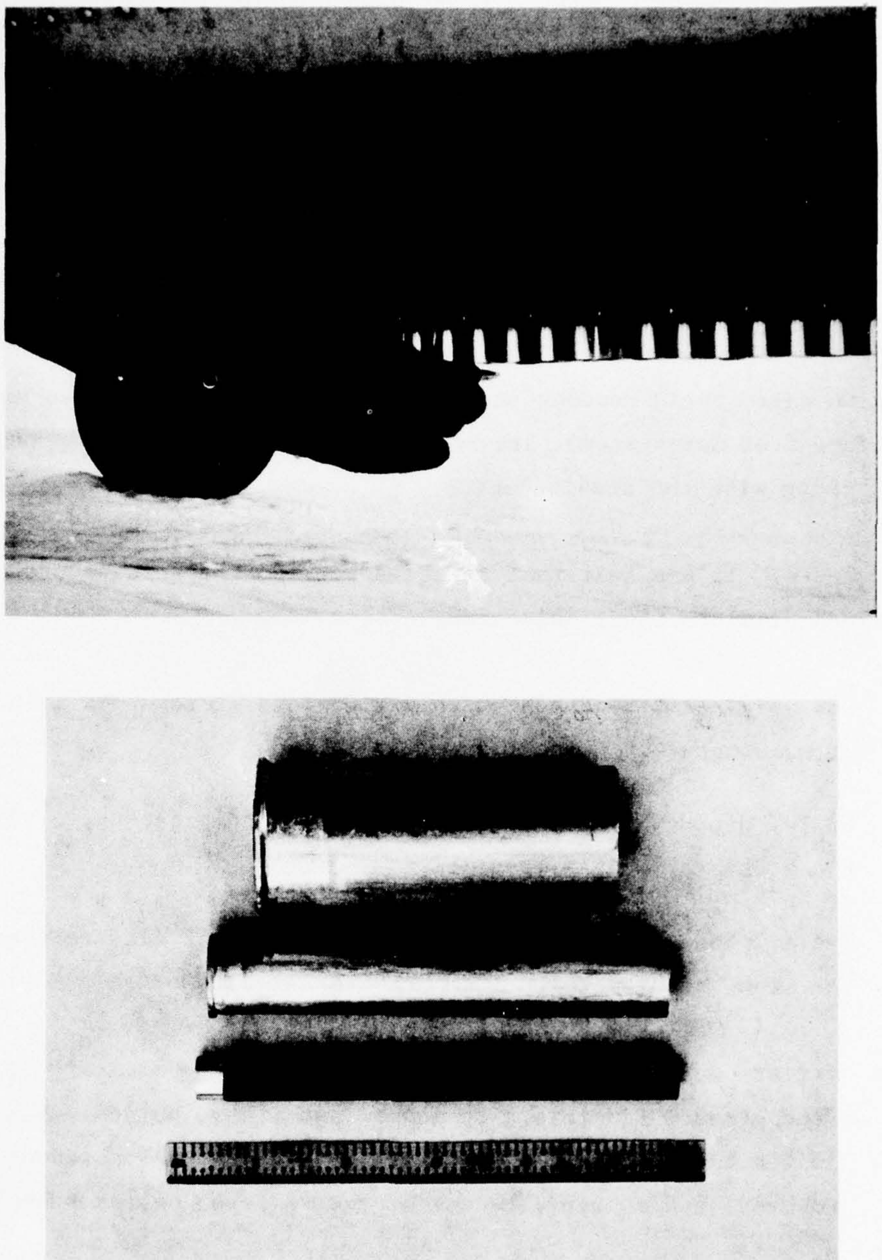

Figure 2a (top). Pyrotechnic seeding rack mounted on the belly of the seeding aircraft. 2b (bottom). Pyrotechnic seeding units. The standard 1 3/8-in diameter unit is at the top of the picture, the NEI 3/4-in diameter unit (used in these tests) is in the middle, and the NWC Stormfury unit is at the bottom.

Questions concerning aging characteristics and storage life were not addressed and would be appropriate as part of the continued development.

Chlorine Doping. The chlorine-doping was developed as a result of the accidental use of a chlorinated binder in pyrotechnics produced by NEI for the Florida Area Cumulus Experiment (FACE). The method developed utilizes a three percent doping of hexachlorobenzene.

Figure 4 compares the test results for the non-chlorinated mixture with the curve from Figure 3. The differences in effectiveness were not as great as expected based on past data, but were in the expected direction. The data for unchlorinated TB-1 were unusually high compared with past tests. The dashed curve in Figure 3 shows the curve previously published by Garvey (1975) for comparison. There is some evidence indicating that unchlorinated tests made following chlorinated tests give higher production curves. Since chlorinated and unchlorinated units were alternated in this series of tests, it may well be that free chlorine in the chamber artificially increased the nucleation effectiveness of the unchlorinated effluent.

A recurring feature of the chlorine-doped formulation should be noted in the figure. That is the virtual plateau in the curve between -8C and -10C. This has apparently been observed in several past tests of the doped compound.

Grain Diameter. The Stormfury unit developed by NWC was designed to take advantage of an increase in effectiveness they predicted would result from reductions in grain diameter. A reduction in coagulation is the suspected cause. Cloud chamber tests of the Stormfury unit verified the expected increase in effectiveness by a factor of two or more.

The results of comparative tests performed in this study are shown in Figure 5. It can be seen that the effectiveness of the larger units seems less at temperatures colder than -16C, but greater at warmer temperatures. The magnitude of difference combined with the small data sample preclude any

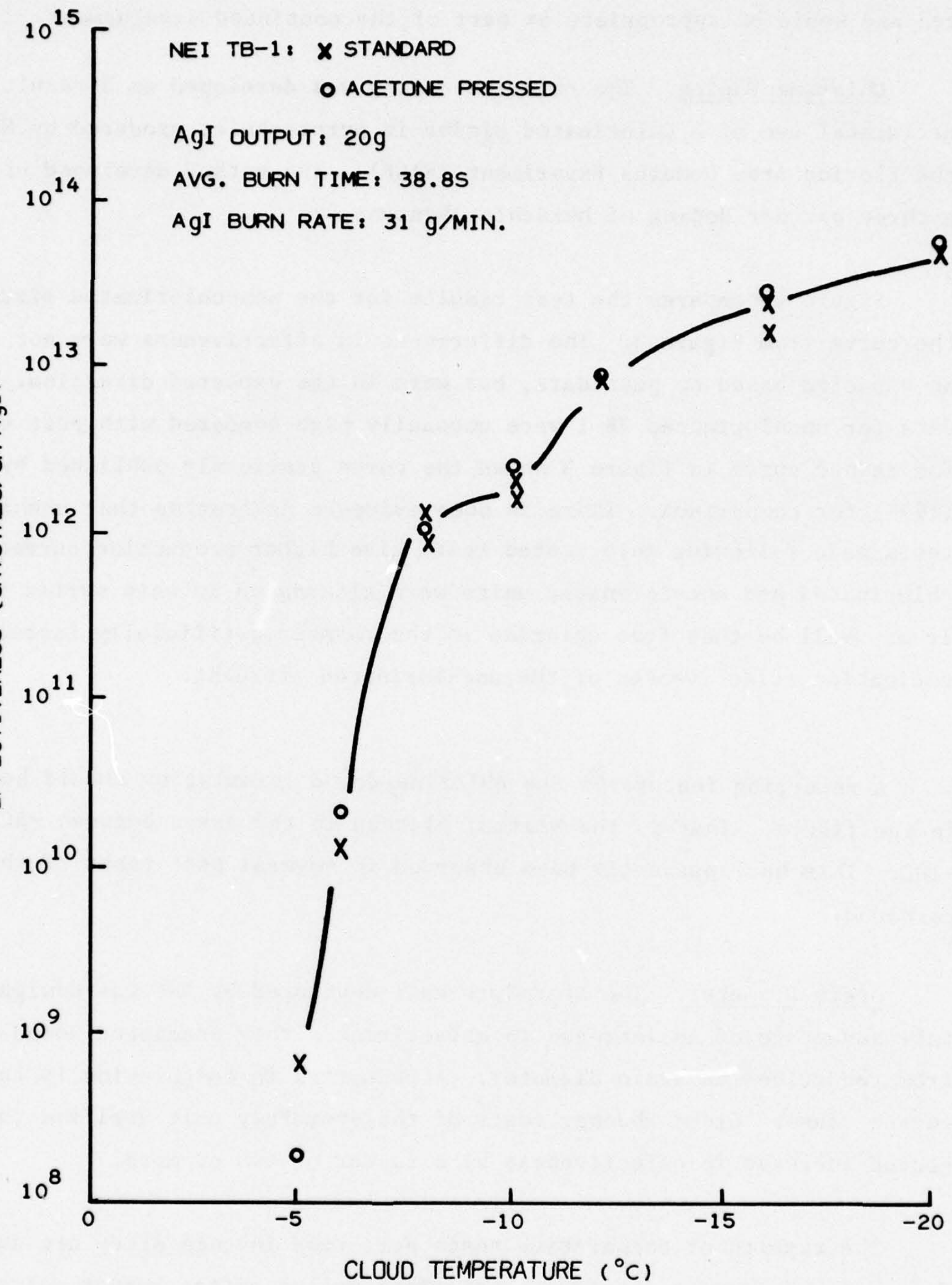

Figure 3. Results of CSU cloud chamber tests of the pyrotechnic units produced using the dry-mix and acetone mix processes.

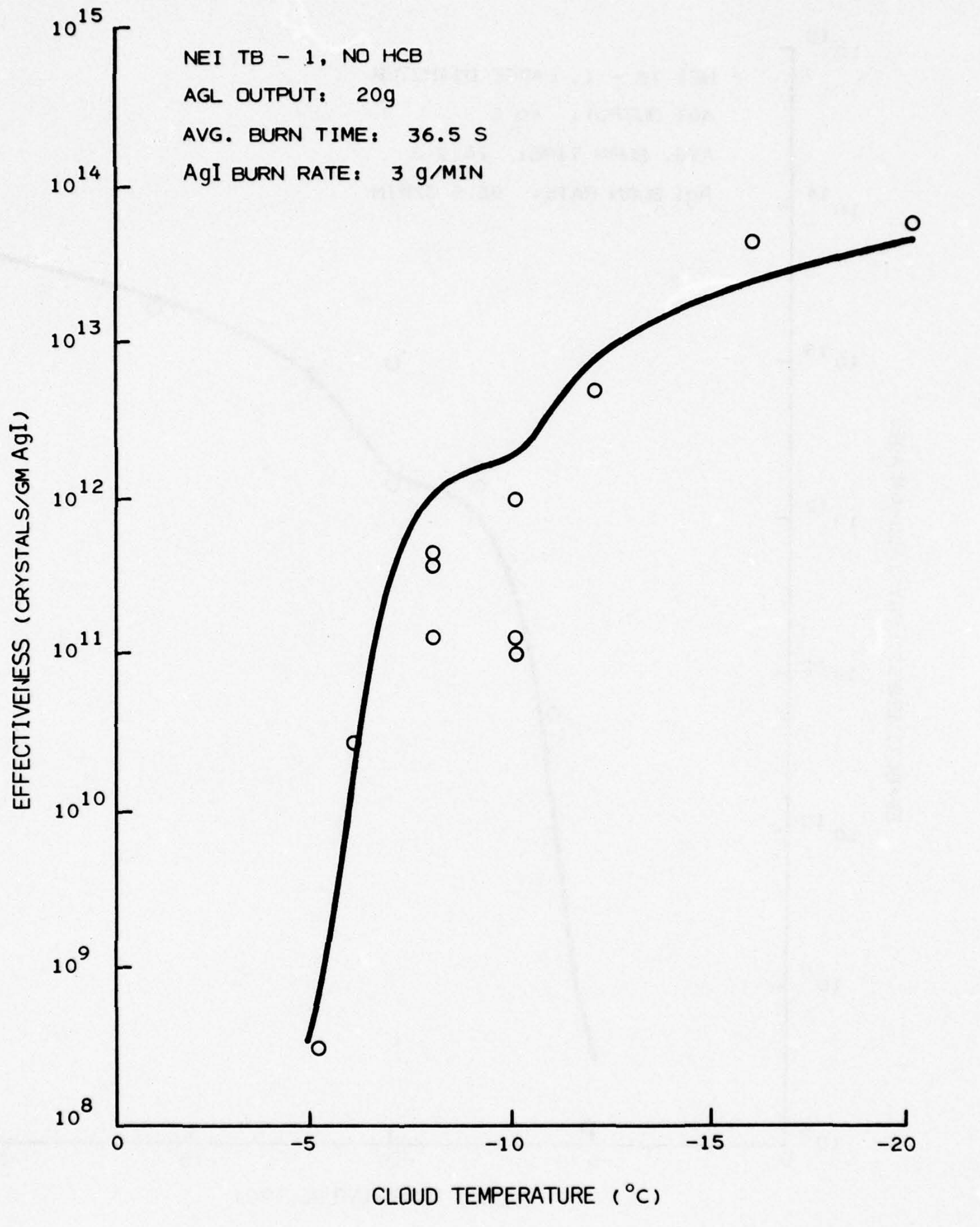

Figure 4. Comparison of cloud chamber results for chlorine-doped and non-doped (no HCB) pyrotechnics. The curve is taken from tests of the standard doped unit (Figure 3). The data points represent the no-chlorine units.

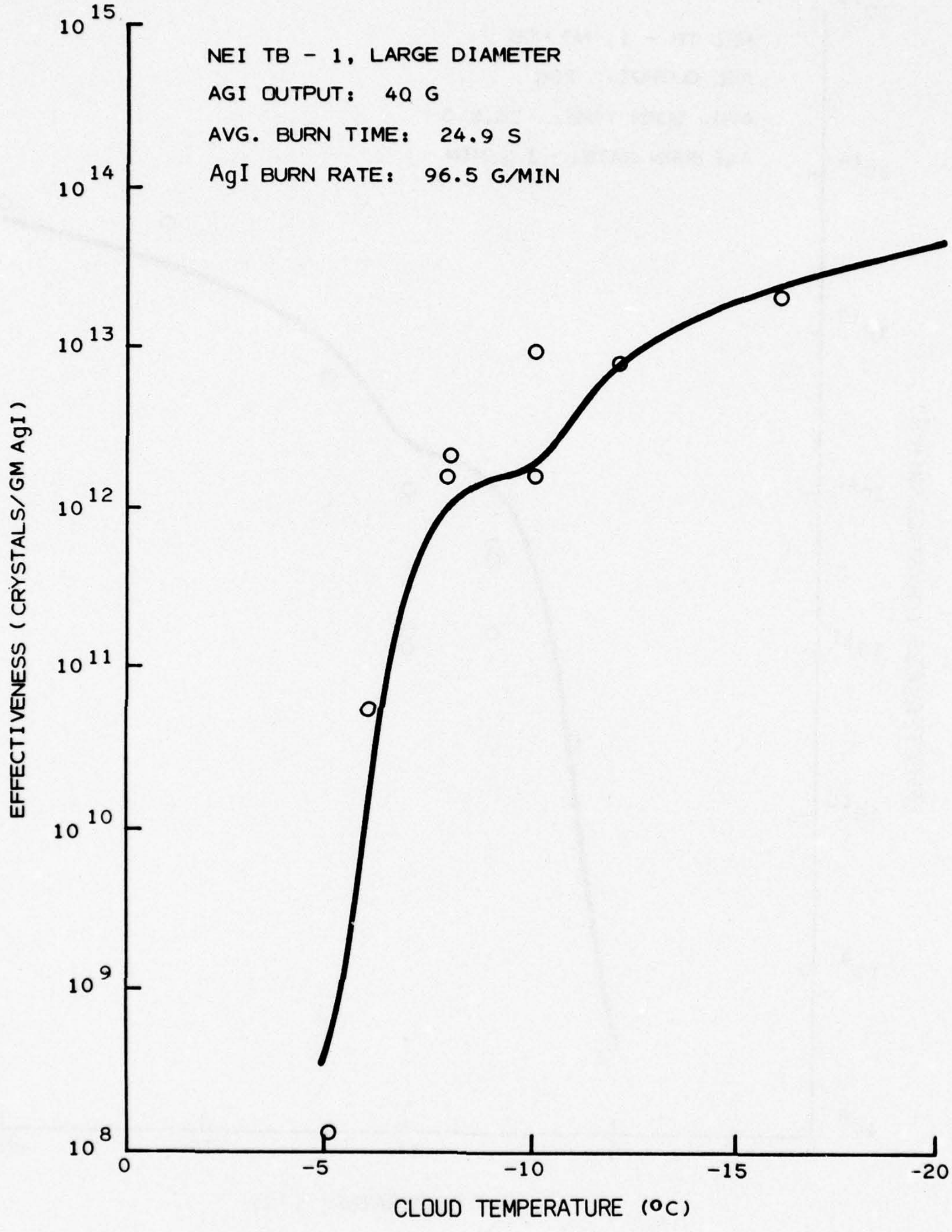

Figure 5. Comparison of the large (1 3/8-in) and small (3/4-in) units. The curve is from Figure 3 for the 3/4-in units. The data points are for the large diameter units.

confident statements. Perhaps the diameter of the NEI unit is not small enough to profit from this phenomenon.

Systems Tests. Several tests were conducted to check the functioning of the overall system. Seeding units ejected from aircraft in clear air at night were observed to insure proper performance. Items of interest included:

1. Reliability of ignition
2. Quality of burn
3. Burn time
4. Fall distance

The results of all tests were satisfactory and confidence was developed that the grains would reliably self-consume before falling beyond the expected level.

4.4 Seeding Rate Calculations

Theoretical estimates can be made of the silver iodide seeding rates that would be required through comparisons with appropriate dry ice dispensing rates determined by Vickers and Church (1966). They found that pellets sized 1 cm x 1 cm x 1.5 cm dispensed at a rate of four pounds $(\text{n mi})^{-1}$ provided an adequate seeding rate. Higher rates made no substantial difference in results. Fukuta et al. (1971) suggest a nucleation efficiency of 8×10^{11} nuclei per gram of dry ice, independent of pellet size over diameters of 0.32-1.91 cm and temperatures from -2°C to -20°C. (Their data actually seem to indicate a somewhat lower efficiency near -2°C, but for our purposes, temperature independence seems a valid assumption.) Using this information we find that the required dry ice seeding rate of 4 lb. $(\text{n mi})^{-1}$ should produce 1.5×10^{15} nuclei $(\text{n mi})^{-1}$.

Chappell and Smith (1976) reported on model calculations of the seeding rate required to clear supercooled stratus. Their calculations were

performed under separate agreement with AFGL. They suggest that a maximum nuclei generating capability of about 200 nuclei per liter would be sufficient for clouds -5C or colder. It is of interest to compare this figure with that derived from experimental data in the preceding paragraph. To do this, we assume that the nuclei dispersed from the seeding aircraft mixes uniformly through a depth of 500 m and a width of 1000 m, which is consistent with the work of Vickers and Church (1966). We may then calculate

$$\frac{1.5 \times 10^{15} \text{ nuclei (n. mi.)}^{-1} \times 10^{-3} \text{m}^3/\ell}{1853 \text{ m (n. mi.)}^{-1} \times 500 \text{ m} \times 1000 \text{ m}} = 1619 \text{ nuclei } \ell^{-1}$$

The two approaches differ by nearly an order of magnitude. The test plan was based conservatively on the results derived from the work of Vickers and Church (1966).

Table 1 shows the results of seeding rate calculations which assume that 1.5×10^{15} nuclei (n mi)$^{-1}$ are required and that the results of the CSU nucleation effectiveness tests (Figure 3) apply. The estimated cost column assumes an average cost of 35 cents per gram of silver iodide.

TABLE 1. CALCULATED SEEDING RATES

Temperature (deg C)	Effectiveness (nuclei g^{-1})	Required Seeding Rate (g AgI (n mi)$^{-1}$)	Est. Cost ($/n mi)
- 5	4.5×10^8	3.3×10^6	-
- 6	1.8×10^{10}	8.3×10^4	29,000
- 8	1.3×10^{12}	1,200	420
-10	2.3×10^{12}	650	230
-12	9.1×10^{12}	170	60
-16	3.5×10^{13}	43	15
-20	4.5×10^{13}	33	12

Several studies show a warm limit of -3 to -4°C for the effectiveness of dry ice in clearing stratus. Since Fukuta et al. (1971) have shown dry ice

to be effective in producing ice crystals to -2°C, we might expect that this warm limit is associated with crystal growth mechanisms other than nucleation. If this is true, no glacogenic material will improve performance at these warm temperatures. Since the chlorinated TB-1 material appears effective starting at -6 to -7°C, there is a gap of 2 or 3°C in cloud temperature which is potentially treatable, but not by the chlorinated TB-1. Other pyrotechnic mixtures have been found to have relatively high efficiencies at these warmer temperatures, among them lead iodide and silver iodide-potassium iodide mixtures. These could potentially be used to fill the gap. It is also possible that the frequency of clouds in this narrow temperature range is small enough that it may be neglected at this stage of development.

5. FIELD TESTS

5.1 Equipment

The project utilized two aircraft, a turbo-charged Cessna 210 and a turbo-charged Piper Aztec. The Aztec dispensed the seeding material and performed various cloud-level measurements. It was provided with deicing equipment to properly cope with conditions encountered in some of the thicker cloud decks. The Cessna 210 provided an observation platform and the command center for direction of the project. The plexiglass in two of the side windows was replaced with clear safety glass to provide distortion-free optics for photography. Ice forming on these windows at the cold temperatures encountered presented a significant problem. This was overcome by providing air ducts to direct air from the cabin heating system directly onto the window.

In addition to the seeding racks previously described, the Aztec was equipped with a Hewlett-Packard programmable calculator (Model 9815) which performed several required functions.

- It provided trigger pulses to the firing circuitry, allowing precise control of the seeding pattern.
- It performed the calculations necessary to obtain the flight level wind in the manner described in a following section.

- It calculated the "optimum" seeding rate observed in the line test based on the time required for the seeding aircraft to traverse from the end of the line to the optimum point and the parameters of the line test.

A Narco DME-190 was installed in the Aztec to provide a precise reading of distance from the navigation aids as is required for the flight level wind measurements.

The aircraft was also equipped with a Meteorology Research Inc. Universal Turbulence Probe, and a facility for measuring free air temperature. The output from the turbulence probe was recorded on a strip chart. Free air temperature was measured by inserting a Mercury thermometer into the slipstream through a tube in the left side window. Care was taken to fly the aircraft at reduced speeds and to shade the thermometer bulb when taking measurements. The effect of dynamic heating on the probe was determined by tests in which measurements were taken over the full range of the aircraft's air speed. It was determined that no significant dynamic heating effect was evident at speeds lower than 120 knots. All temperature measurements were taken in clear air.

FM radios were installed in both aircraft to provide a separate radio link for technical communications. Other traffic on these frequencies rendered this link ineffective. The technical communications were kept to a minimum and transmitted via air traffic control frequencies.

5.2 Test Procedures

All tests were performed during daylight hours (approximately 0600-1800 local time) to allow photographic documentation. Potential ground target locations in the study area were documented both photographically and by VOR/DME coordinates prior to the beginning of any tests.

Supercooled stratus decks were selected that were expected to persist for a minimum of three hours. Cloud decks to an altitude of 15,000 feet were considered potential candidates for seeding experimentation. The cloud

base was required to be 1000 feet or more above the ground to provide a margin of safety should the pyrotechnics fall somewhat further than expected.

Standard Procedures. Each field test began with an empirical determination of the optimum seeding rate. The seeding aircraft would fly a straight flight track normal to the mean wind just above cloud top. Pyrotechnics were fired by the programmable calculator at varying intervals to provide linearly decreasing concentrations. The seeding aircraft crewmen operated this pre-program system under the direction of the project meteorologist. Figure 6 provides a schematic representation of a typical flight track. Photographs of the results of these drops were obtained from the observing aircraft's vantage point. The point drops merged into the appearance of a seeded line in most situations. The optimum spacing between drops was determined from the observing aircraft's vantage point within about thirty minutes after beginning the seeding. In order to determine the spacing of the pyrotechnic drops, the seeding aircraft flew through the cleared area at a constant speed, beginning at the high concentration end. The observing aircraft noted the time required for the seeding aircraft to traverse the distance from the end of the line to point of optimum seeding. The seeding interval producing optimum results was then determined from this time and parameters of the seeding run. The calculation was performed by the H-P calculator.

The optimum spacing of pyrotechnics determined in the seeding rate test was utilized in the determination of the optimum spacing of seeding lines. Flights tracks were flown parallel to each other at varying distance intervals in order to establish the optimum spacing of lines for which the parallel seeded lines would join to form a cleared area. The optimum spacing was determined from the observing aircraft. Photographic records provided documentation of the tests. A typical flight pattern is provided in schematic form in Figure 7. The length of the line in the rate test was either one or two nautical miles. The seeded lines in the raster test were about three miles in length with a total pyrotechnic expenditure of from 50 to 200 units during each test depending upon the concentration and the number of lines.

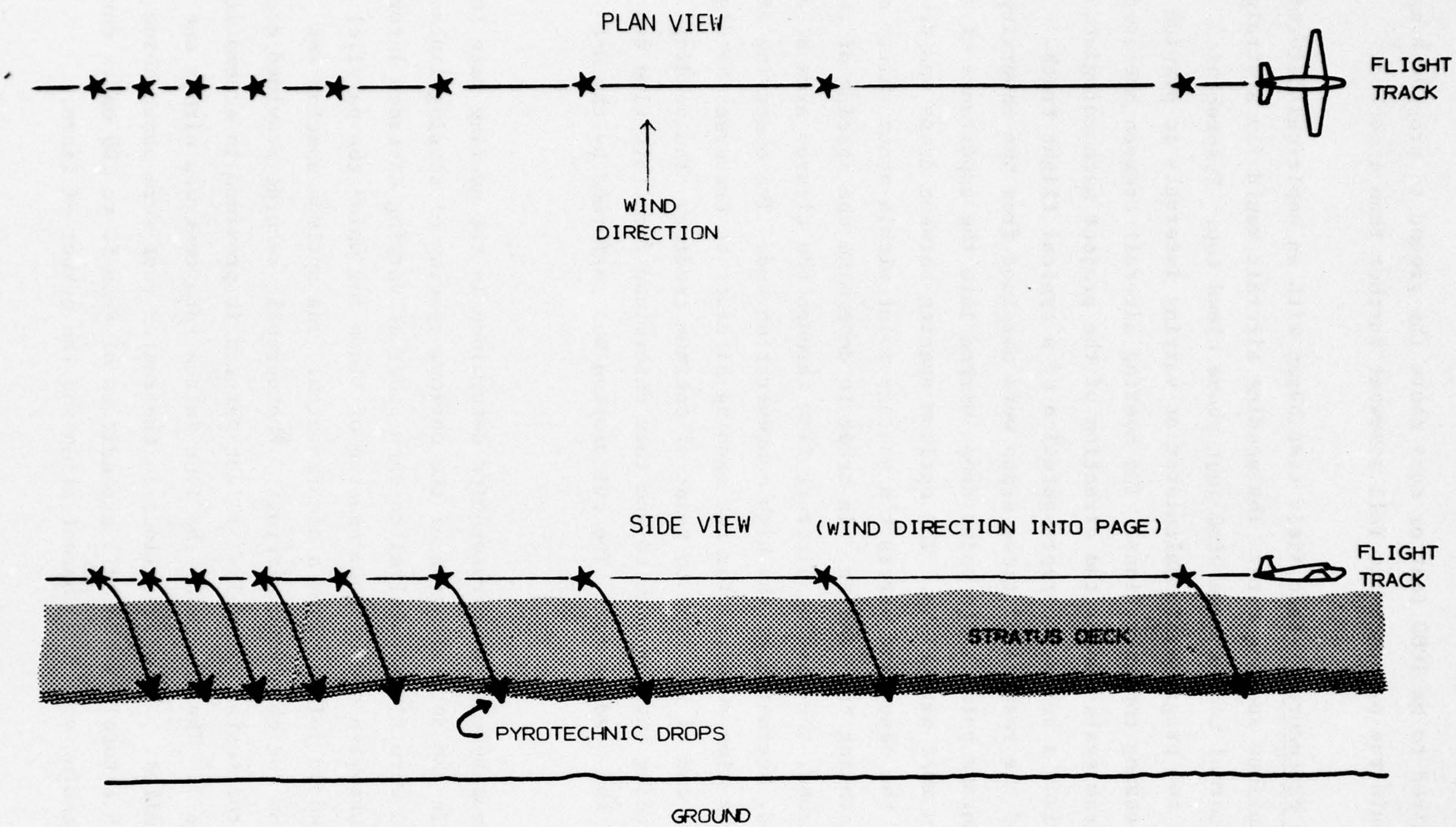

Figure 6 Seeding rate flight pattern.

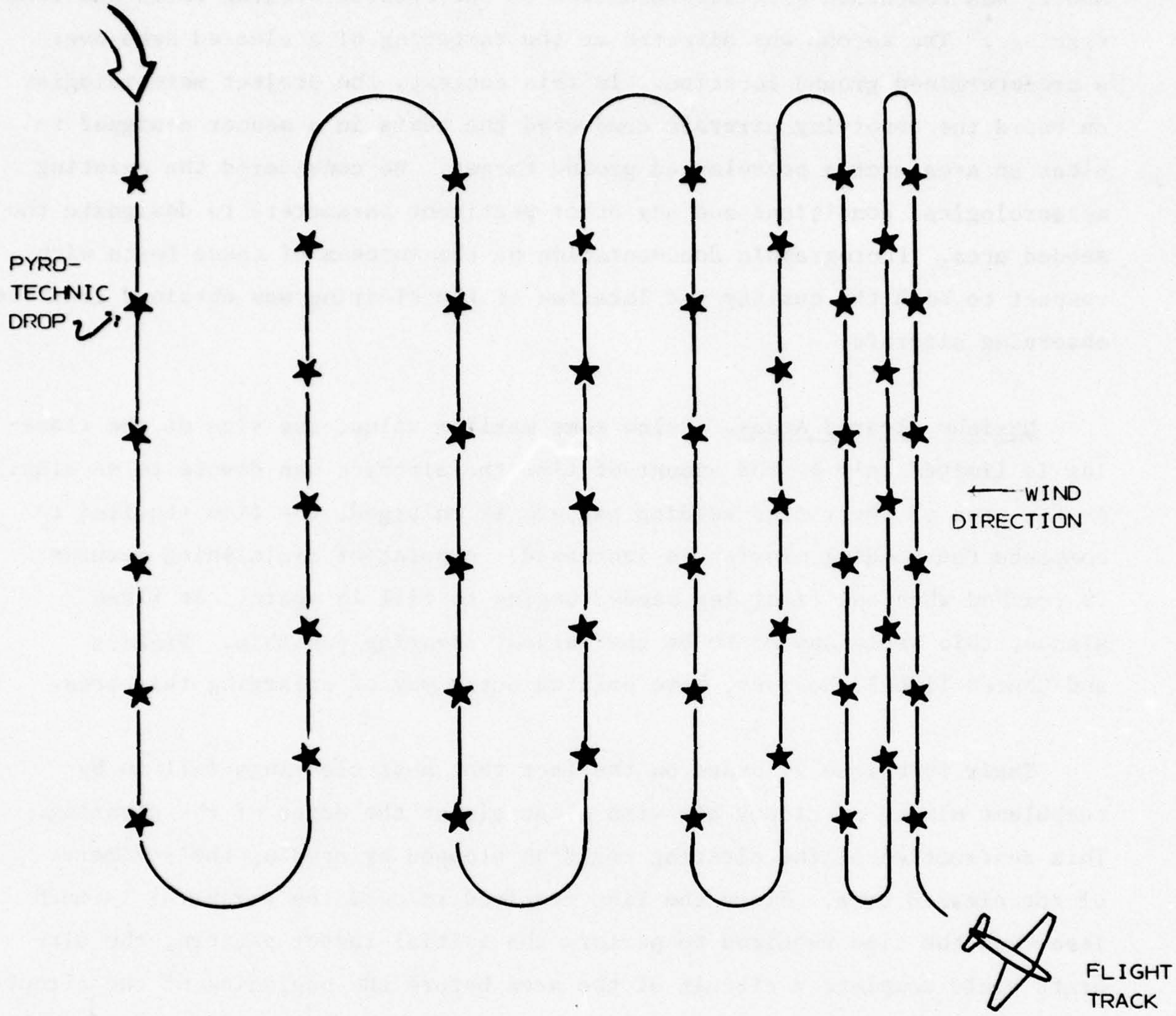

Figure 7. Seeding line flight pattern.

These tests were performed with a dual purpose. The first, as stated above, was concerned with determination of the optimum seeding rates and line spacings. The second was directed at the targeting of a cleared area over a predetermined ground location. In this context, the project meteorologist on board the observing aircraft conducted the tests in a manner designed to clear an area over a preselected ground target. He considered the existing meteorological conditions and any other pertinent parameters to designate the seeded area. Photographic documentation of the success of these tests with respect to both the quality and location of the clearing was obtained from the observing aircraft.

Maximum Cleared Areas. Below some maximum value, the size of the clearing is limited only by the amount of time the aircraft can devote to seeding. As the area of the raster seeding pattern is enlarged, the time required to complete the seeding mission is increased. A point of diminishing returns is reached when the first leg seeded begins to fill in again. At first glance, this would appear to be the largest clearing possible. Vickers and Church (1966), however, have pointed out a way of enlarging this area.

Their technique is based on the fact that most clearings fill in by turbulent mixing of cloudy air with clear air at the edges of the clearing. This destruction of the clearing could be stopped by seeding the perimeter of the cleared area. Since the time required to seed the perimeter is much less than the time required to perform the initial raster pattern, the aircraft would complete a circuit of the area before the beginning of the circuit began to refill. By then expanding the size of the seeding pattern, it would be possible to gradually increase the clearing size. The limiting size would be reached when the time required for the aircraft to complete one circuit of the area equalled the time required for the cloudy air to mix into the clearing a distance equal to the width of the clearing produced by one seeding pass.

Because of the sparsity of appropriate meteorological conditions, all efforts in these tests had to be directed towards the standard test procedures in order to obtain a significantly large sample of these tests. There was

unfortunately no opportunity under these conditions to attempt the clearing of maximum size. This test should be incorporated into any future work.

Aircraft Measurements. Before each test, the seeding aircraft measured the temperature and wind at cloud top, then descended through the cloud while taking turbulence measurements, and observed the temperature at cloud base. While making temperature measurements, the aircraft was flown at slow speed and the temperature probe shaded from the sun to avoid aerodynamic heating and insolation errors. The aircraft descended through the cloud with engines throttled back to avoid errors in the turbulence measurements due to engine vibration. During actual seeding runs the seeding aircraft was flown at a relatively low speed of about 120 knots.

The observing aircraft typically flew at 5000 to 6000 feet above cloud top to obtain a good overall vantage point of the operation. All relative aircraft location and meteorological data (except turbulence data) were recorded by the seeding aircraft crewman. Audio tape recorders were provided for each aircraft for comprehensive note taking. Critical data were also recorded in writing.

Typical Operational Scenario. To facilitate the visualization of field operations, a typical operational day schedule is given below. If favorable meteorological conditions persisted on a given day, more than one experimental sequence was sometimes accomplished.

- 12-24 hour forecast of suitable conditions (i.e., supercooled stratus over the target area).
- Notification of crew and other concerned individuals and agencies of impending operation.
- 8-12 hour forecast update.
- Declaration of potential "go" conditions by project meteorologist.
- Scheduling of operations by project meteorologist. Selection of potential target area.

- Acquire aircraft clearances. Perform preflight checks of aircraft and seeding systems. Inform appropriate FAA Flight Service Station and Air Traffic Control Center of Operation and potential target.

- Observation aircraft takeoff and climb-out to 5000-6000 feet above cloud tops.

- Seeding aircraft takeoff and climb-out to cloud top.

- Final selection of target by project meteorologist from observing aircraft. Target selected is recorded on date/comments board next to photo clock in observation aircraft. Confirm final seeding area with FAA.

- Seeding aircraft positioned in general area of pre-selected ground target.

- Seeding aircraft measurement sequence (cloud top and base temperatures, winds, and in-cloud turbulence).

- Notification to conduct seeding rate test given to seeding aircraft by project meteorologist (parameters for seeded line specified by project meteorologist).

- Seeding aircraft flies seeding rate test.

- Seeding aircraft flies through cleared area to provide distance information necessary to allow the project meteorologist to determine optimum pyrotechnic spacing.

- Photographic documentation of seeding rate tests from observing aircraft.

- Decision made to proceed with seeding pattern test given to seeding aircraft by project meteorologist. Optimum seeding interval specified by project meteorologist.

- Seeding aircraft flies seeding pattern test.
- Photographic documentation of seeding pattern test.
- Seeding aircraft returns to base or alternate upon instructions from project meteorologist.
- Observing aircraft continues monitoring of cleared area.
- Observing aircraft returns to base or alternate.
- On-site briefing of day's operations conducted by project meteorologist.
- Preparation of preliminary logs of operations including transcribing of recorded voice tape if time allows.
- Stand-down.

5.3 Personnel

The co-principal investigators on this project were Chester Wisner and John Thompson. Both of the co-principal investigators were personally on-site for the field tests. Mr. Thompson, who was field project director, conducted all of the field tests. Mr. Wisner was on-site during the first two weeks of the field tests. Pilots for the aircraft were provided by Northwestern Michigan Aviation. Mr. Peter Morrison piloted the seeding aircraft, and Mr. William Fahl piloted the observation aircraft. The seeding aircraft crewman was Airman Brian Walker. Airman Walker was provided to the project by AFGL. Mr. Nick Vincent of Rex Fleming Productions, was the project photographer.

6. OPERATIONS

6.1 Summary of Operations

The field crew departed Santa Barbara in the project aircraft January 20 arriving in Minneapolis on January 23. A coordination meeting was held with FAA personnel from the Minneapolis Air Traffic Control Center on January 23. The crew then continued on to Traverse City arriving that evening.

Operations began on February 2, 1977, and continued through March 6. A period of down-time from February 6 through 15 was encountered as a result of a tubro-charger oil pump failure on the Aztec, complicated by the failure of the supplier to promptly ship a replacement part. Few opportunities for operations occurred during this time as inappropriate conditions (either too little cloudiness or storms) prevailed on eight of the ten days the aircraft was down. Table 2 summarizes the pertinent meteorological and seeding parameters associated with each test. It also indicates the degree of success of each test.

Eleven flights were conducted on ten separate days. Ten seeding rate tests and five seeding pattern tests were conducted. On only one day (February 22) was it not possible for the seeding to induce any clearing effect. Cloud temperatures on this day were -6°C and warmer. Five of the tests were targeted successfully, and five were observed to miss the target. The remaining tests were either not targeted, or it was not possible to determine whether they had hit the target.

The following section describes each test individually. Photographs illustrating relevant features of the treated areas at various times of development have been included where applicable.

FEBRUARY 5, 1977

Target: Manistee County Airport

Seeding site: Area 320°/13 n mi (24 km) from Manistee

Computed winds at cloud top: 330°/21 kts

Weather situation: Surface low in southern New England with cyclonic flow at the surface and aloft. Upper trough over eastern Michigan and Ohio.

Cloud Data:

Type: Slightly convective stratocumulus. Solid over Lake Michigan and broken to scattered over land areas.

Height-temperature: Top 4900 ft (1.49 km), -21.5°C
Base 3300 ft (1.01 km), -19.0°C
Depth 1600 ft (.49 km)

TABLE 2 SUMMARY OF OPERATIONS

		Results						Seeding Rate	Temperature			
Date	Target	Clearing	Targeting	Operation	Number of Lines	Length of Lines (n mi)	Flares per line	g AgI (n mi-Kft)$^{-1}$	Cloud Top °C	Cloud Base °C	Cloud Top Height ft MSL	Cloud Depth ft
Feb 5	Manistee Airport	Inconclusive	Missed	Line Test	1	2	13	50 to 5	-21.5	-19.0	4,900	1,600
Feb 16	None	Yes	-	Line Test	1	1	36	300 to 30	-17.0	-17.5	3,700	900
Feb 17	Roscommon Airport	Yes	Inconclusive	Line Test	1	1	11	80 to 8	-15.5	-13.5	10,400	2,400
	Roscommon Airport	Yes	Missed	Raster	3	2	19	44	-17.5	-13.5	11,000	3,000
Feb 18	Roscommon Airport	Yes	Missed	Line Test	1	1	24	200 to 20	- 9.5	approx - 3.0	6,500	approx 4,000
	Roscommon Airport	Yes	Hit	Raster	3	3	19	30	- 8.5	approx - 3.0	6,000	approx 3,500
Feb 19	Atlanta Airport	Yes	Missed	Line Test	1	2	18	70 to 7	-12.0	-10.5	4,500	1,700
Feb 22	Otsego Airport	No	-	Line Test	1	1	24	200 to 20	- 6.0	- 6.0	3,700	900
		No	-	Line Test	1	1	24	200 to 20	- 3.0	- 4.0	4,500	1,300
Feb 26	None	Yes	-	Line Test	1	1	12	90 to 9	-14.0	-11.5	4,200	1,500
	Kincheloe AFB	Yes	Hit	Raster	5	3	23	36	-11.0	-11.5	5,200	2,500
Mar 5	Roscommon Airport	Partial	Hit	Line Test	1	1	36	300 to 30	- 8.5	- 3.0	8,500	6,200
Mar 6	Roscommon Airport	Partial	Missed	Line Test	1	2	24	100 to 10	- 9.0	- 4.5	6,200	4,000
		Yes	Hit 1)	Raster	3	3	43	70	-10.0	- 4.5	6,500	4,300
Mar 6	Roscommon Airport	Yes	Hit	Raster	4	3	49	80	- 9.5	- 4.5	6,700	4,500

1) Clearing occurred after seeded area passed target.

Seeding Rate Test Data:

Agent: 10-gm AgI pyrotechnic flares

Pattern: Line, 2 n mi (3.7 km) long

Concentration: 50 to 5 gm $(\text{n mi - Kft})^{-1}$

Output: 13 flares dispensed, 130 gm AgI total

Drop altitude: 5000 ft (1.52 km)[1)]

Time: 1255 EST

Results:

The response to seeding was slow; the first evidence of glaciation was noted 23 minutes after seeding. In this region a trough developed in the clouds with the cloudiness in the trough composed of a mixture of ice crystals and water cloud. At this time the glaciated area was about 4 km long and about .25 km wide. After 40 minutes the line was clearly defined with a hard edge as the ice crystals in the seeded area descenced below the main cloud deck. The seeded area drifted with the wind towards land and, after 45 minutes, was along the eastern shore of Lake Michigan. At this time there was evidence of a small hole in the seeded area through which the ice covering Lake Michigan could be seen. At the same time, however, several other natural holes began to appear in the cloud deck as it began to break up along the edge of the lake. Further observation of the seeded area was abandoned at that time. At the end, the seeded area was still composed of a mixture of ice crystals and considerable water cloud. It had been assumed that with the cold temperatures observed in the cloud deck, the relatively low concentration of 50 to 5 gm $(\text{n mi - Kft})^{-1}$ would be sufficient to dissipate the clouds in the treated area. The slow response time and the fact that much of the treated area was still composed of water cloud at the time of the breakup would suggest that the concentration should have been higher. It is noted that the treated area tended to remain as a relatively narrow line and did not expand into a circular area as did most of the seeded areas in subsequent tests. From the initial point of seeding, the treated area moved from 345°

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1) - All heights are MSL.

at the speed of 21 kts instead of the calculated wind of 330°/21 kts. This 15° error in the calculated wind caused the seeded area to miss the target. The treated area was nine kilometers south of the Manistee Airport at the end of the test.

FEBRUARY 16, 1977

Target: None

Seeding site: Area 006°/39 n mi (73 km) from Traverse City, Michigan

Computed winds at cloud top: None

Weather situation: Surface high pressure centered over Minnesota with anti-cyclonic flow surface and aloft through 700 mb. Weak trough over Michigan at 500 mb.

Cloud Data:

Type: Stable stratocumulus. Solid in patches over Lake Michigan with mostly clear conditions over surrounding land areas.

Height-temperature: Top 3700 ft (1.13 km), -17.0°C
Base 2800 ft (.85 km), -17.5°C
Depth 900 ft (.27 km)

Seeding Rate Test Data:

Agent: 10-gm AgI pyrotechnic flares

Pattern: Line, 1 n mi (1.8 km) long

Concentration: 300 to 30 gm $(\text{n mi - Kft})^{-1}$

Output: 36 flares dispensed, 360 gm AgI total

Drop altitude: 4500 ft (1.37 km)

Time: 1737 EST

Results:

In this test the response to seeding was rapid and definite. After three minutes the seeded area exhibited glaciation along the entire length of the seeded line. At the end of 13 minutes, the treated area appeared as a rectangle and small holes began to appear in the seeded area (see Figure 8) and by 20 minutes the ice on Lake Michigan was clearly visible through large

Figure 8. Stable stratocumulus 13 minutes after seeding February 16, 1977. Seeded area has increased to about 6 km^2 (2 x 3 km).

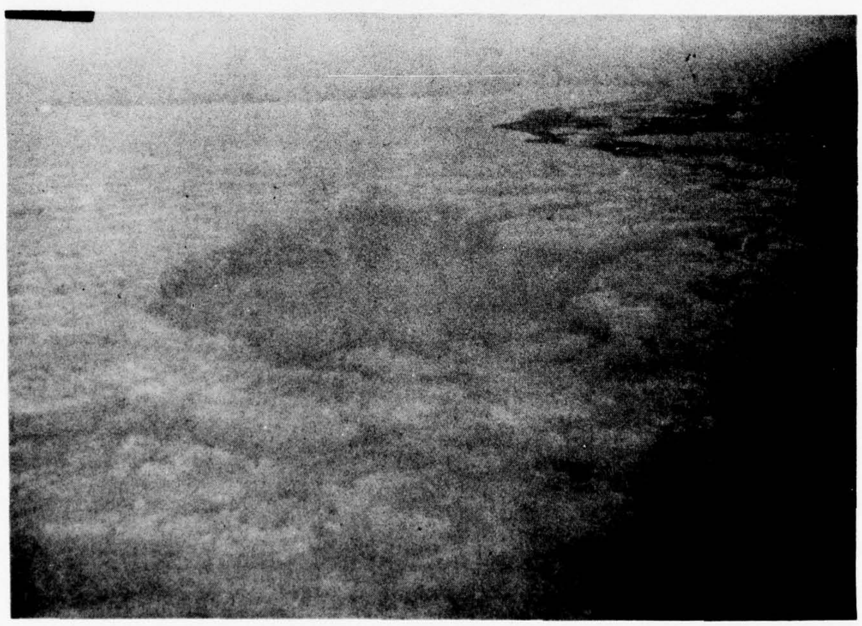

Figure 9. Seeded area 25 minutes after seeding. Area size approximately 9 km^2.

breaks in the cloud deck. Twenty-five minutes after seeding, the treated area had increased in length from 1.8 km to almost 3.5 km, and as can be seen in Figure 9, the width of the initial narrow line had grown to almost 2.7 km with the whole seeded area assuming an elliptical shape. With darkness rapidly approaching, observations had to be terminated; however, at 33 minutes the observation aircraft made a VFR descent through the seeded area. At that time, the seeded area was about two miles in diameter, and was nearly devoid of clouds except for a few small patches of ice crystals. It would seem that the concentration used was more than adequate to treat the cloud deck with the thermal conditions that were observed.

FEBRUARY 17, 1977

Target: Roscommon County Airport

Seeding site: Area 300°/20 n mi (37 km) from Roscommon County Airport

Computed winds at cloud top: 300°/28 kts

Weather situation: Surface high pressure over the Ohio Valley with a ridge at the surface and aloft over the region.

Cloud Data:

Type: Altocumulus/altostratus, solid over entire area

Height-temperature: Top 10,400 ft (3.17 km), -15.5°C
Base 8000 ft (2.44 km), -13.5°C
Depth 2400 ft (.73 km)

Seeding Rate Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: Line, 1 n mi (1.8 km) long

Concentration: 80 to 8 gm $(\text{n mi} - \text{Kft})^{-1}$

Output: 11 flares dispensed, 220 gm AgI total

Drop altitude: 11,500 ft (3.51 km)

Time: 1258 EST

Results:

Response to seeding was rapid. Five minutes after seeding, a change in cloud texture on a line about 2 km in length was noted. At seven minutes, a

clear indentation or slot in the clouds was evident (Figure 10). Resolution of the 35-mm still picture taken at that time by utilizing the photogrammetric technique (Appendix C) suggests that the glaciated area measured about 2.5 km long. The width averaged about .5 km, varying from .8 km at the high concentration end to .3 km at the low concentration end of the line. Ten minutes after seeding, the rectified photograph shows that the glaciated area had grown to measure 1.2 km wide and 3 km long. By 13 minutes, the glaciated area was taking on an elliptical shape with a width of 2.5 km and a length of 3.6 km. This was about twice the original length of the seeded line. Two minutes later these dimensions were 2.5 km wide and 4.7 km long. This development can be seen in Figure 11.

Twenty-five minutes after seeding (Figure 12), the area had assumed an almost circular shape with a diameter of nearly 6 km. It contained a mixture of ice crystals and water cloud, but no breaks in the cloud deck were visible. At 30 minutes, some holes large enough that portions of the ground could be seen were apparent. One large hole which measured 4 km by .5 km was located on the edge of the glaciated area adjacent to the untreated cloud. At this time the glaciated area was almost 7 km across. The seeded area was tracked for another ten minutes to a point that was thought to be about 18 km west of the intended target (Figure 13). This suggested that the actual winds were more northwesterly than had been anticipated, and it appeared that the seeded area would not hit the target. (Actually a navigational tracking error had been made which indicated the seeded area further west than it really was, but this error was not discovered until much later in the flight.) With the result of the seeded line producing some clearing and on the basis of the apparent movement of the seeded line, it was decided to make a seeding pattern test using a three-line raster pattern moving the seeding site further northwestward from the intended target. The visual evidence suggested that the time for best clearing along the line occurred about halfway down the line. With the concentrations used in the seeding rate test, this worked out to be about 44 gm $(\text{n mi} - \text{Kft})^{-1}$.

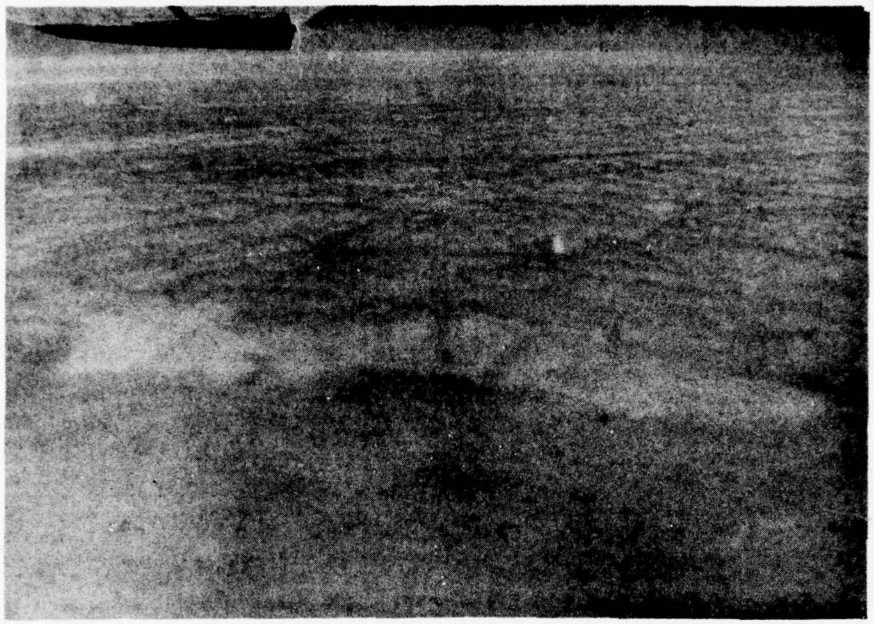

Figure 10. Altostratus and altocumulus seven minutes after seeding February 17, 1977. Seeded line is about 2.5 km long.

Figure 11. Seeded area 15 minutes after seeding. The glaciated region has grown to a rectangle about 2.5 km wide and 4.7 km long.

Figure 12. Seeded area 25 minutes after seeding. The glaciated area was almost circular with a diameter of nearly 6 km.

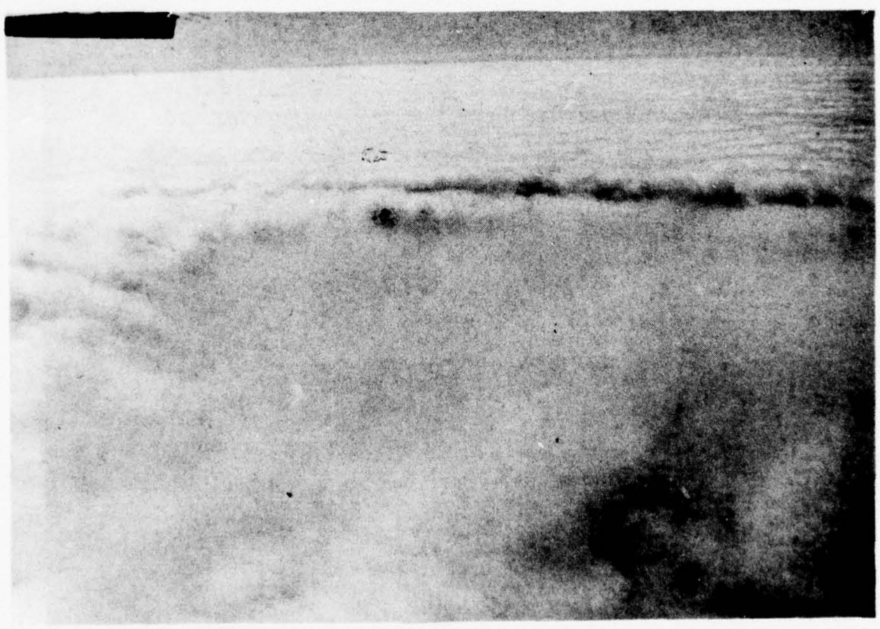

Figure 13. Seeded area 39 minutes after seeding. Portions of the ground were visible through several holes in the treated area but not evident from an oblique view.

At 1345 EST the aircraft broke off tracking the first seeded area and flew to the area where a three-line raster was to be made. The target remained the Roscommon County Airport with the following data as inputs into the seeding decision.

Seeding site: Area 335°/20 n mi (37 km) from Roscommon County Airport

Computed winds from tracking: 335°/24 kts

Cloud Data:

Type: Altocumulus/altostratus

Height-temperature: Top 11,000 ft (3.36 km), -17.5°C

Base 8000 ft (2.44 km), -13.5°C

Depth 3000 ft (.91 km)

Seeding Pattern Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: 3 parallel lines, each 2 n mi (3.7 km) long: 1 n mi (1.8 km) spacing between lines 1 and 2, and 1.4 mi (2.6 km) spacing between lines 2 and 3. Total raster size: 2 n mi x 2.4 n mi (3.7 km x 4.4 km).

Concentration[1)]: 44 gm $(\text{n mi} - \text{Kft})^{-1}$

Output: 19 flares per line (total 57), 1140 gm AgI total

Drop altitude: 12,000 ft (3.66 km)

Time: 1410 EST

Results:

Within seven minutes the area where the cloud deck was seeded was clearly visible (Figure 14) as three glaciated lines in the cloud. At 11 minutes, the first and second lines were beginning to merge (see Figure 15), although there was still a narrow ridge of water cloud (< .5 km wide) between them. There was also evidence of merger between the second and third line at this time with the water cloud ridge measuring between .5 and 1.0 km in width.

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1) Due to malfunction, two flares in line 1 did not fire and three flares in line 2 did not fire. All 19 flares in line 3 fired. Thus, total concentration in lines 1 and 2 was slightly less than 44 gm $(\text{n mi} - \text{Kft})^{-1}$.

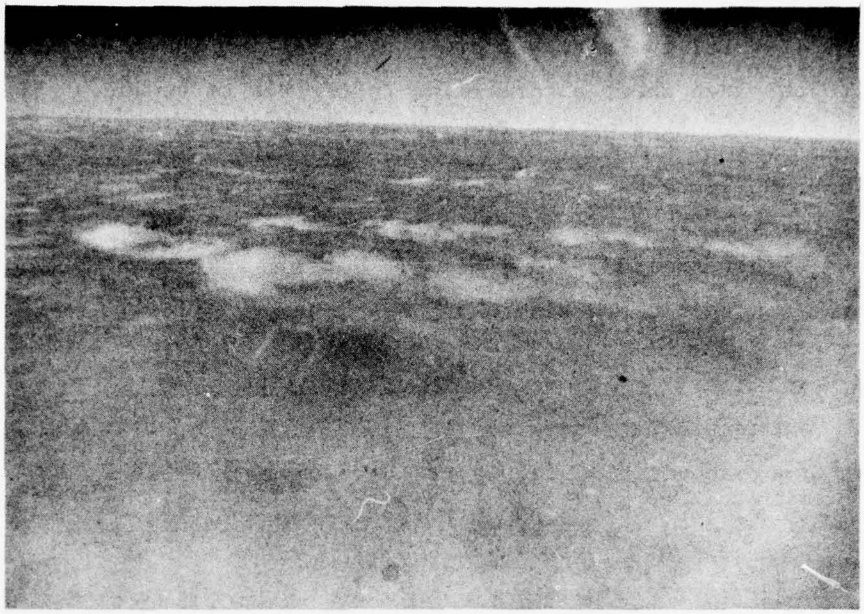

Figure 14. Altostratus and altocumulus seven minutes after seeding. The clouds were seeded in a pattern consisting of three parallel lines each 3.7 km long and spaced 1.8 km and 2.6 km apart. Lines 1 and 2 are evident in the center of the picture with line 3 located just below the horizon.

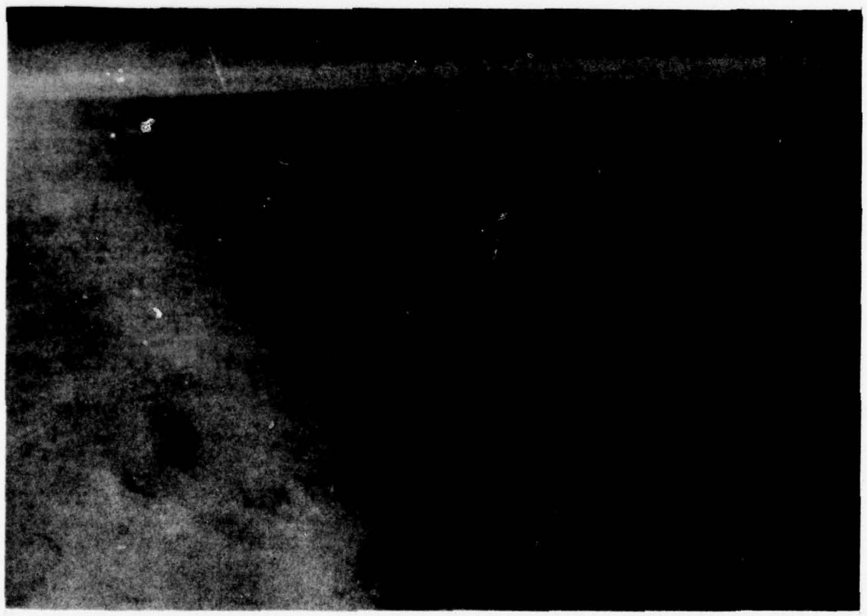

Figure 15. Seeded area 11 minutes after seeding. Note that the unglaciated cloud region between line 1 (to the right) and line 2 has decreased to less than 0.5 km.

By 17 minutes (Figure 16), the first and second lines had completely merged, but a substantial ridge of water cloud still existed between the second and third lines.

At this point, the observation aircraft made a flight back to the original rate test seeded area. This was now over an hour and a half after seeding. It appeared as a large circular area composed mostly of ice crystals or clear areas with some water cloud in the center of the circle (Figure 17). Looking straight down (Figure 18), the ground was visible through much of this area, but there were enough suspended ice crystals in the "hole" that the oblique view from a distance did not reveal any ground targets. Rectification of the photography indicated that the glaciated area had grown in size to between 11 and 12 km in diameter. There was evidence that the clouds were beginning to reform with a ridge of water cloud about 1 km wide splitting the hole about one third of the way from the edge. It was at this time that the navigational error was discovered as the position of the seeded area was determined to be 20 km southeast of the Roscommon County Airport. This meant that the track of the first seeded area had been almost on target drifting on a course from 290° at a speed of 19 kts. This also meant, of course, that the second seeded area would pass to the north of the target since the seeding site had been shifted northward and eastward from the first one.

The observation aircraft returned to the second seeded area at 38 minutes after seeding. By this time, the third line had started to merge in with the other two, and the seeded area had become a large ellipse (see Figure 19). Portions of the ground were visible through small clearings within the treated area, particularly in those sections of the area near the wall (Figure 20) of the untreated cloud surrounding the treated area. Shortly after this, at the 45-minute mark, a radar fix established that the second seeded area was 26 km north-northeast of the target. This movement was computed to be 290° at 20 kts which agreed with the movement of the first seeded area and was very close to the original computed wind. Fifty minutes after seeding, the treated area had several large holes in it,

Figure 16. Seeded area 17 minutes after seeding. Lines 1 and 2 have completely merged but line 3 remains separated.

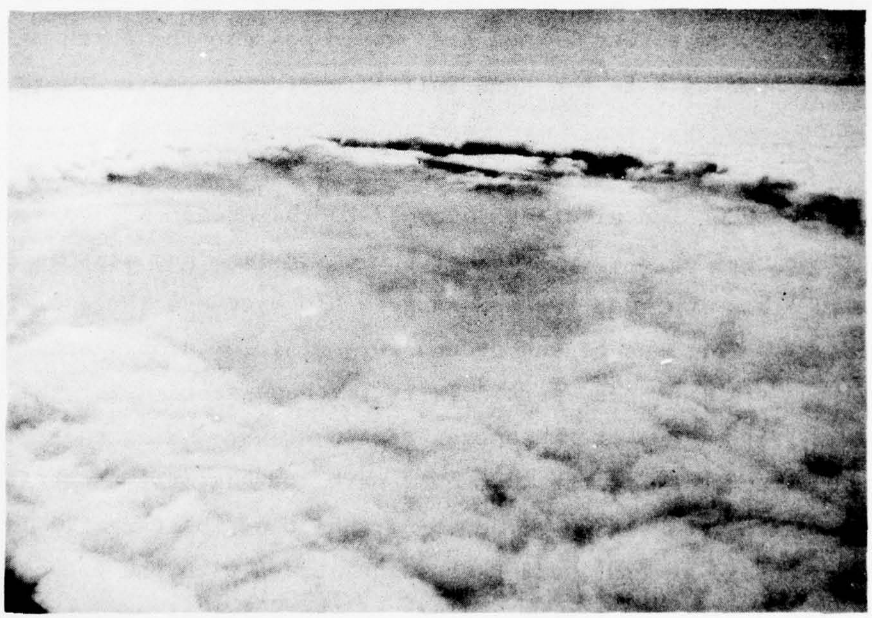

Figure 17. The first seeded area (one line 1.8 km long) 95 minutes after seeding. The treated area has grown to a circle nearly 12 km in diameter.

Figure 18. The first seeded area 99 minutes after seeding. Note ground features visible through clear areas.

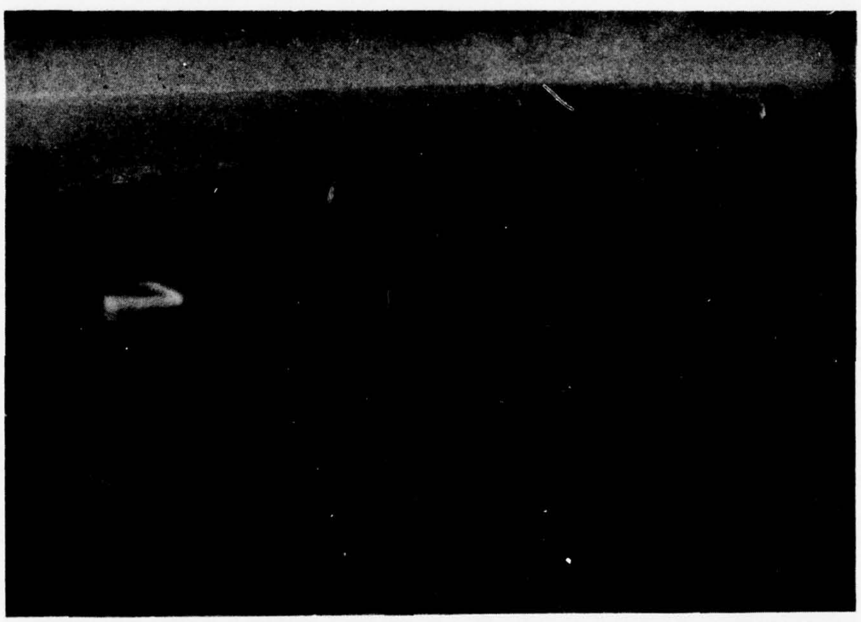

Figure 19. The second seeded area (the three line raster) 38 minutes after seeding. Portions of the third line are merging with the first and second lines.

Figure 20. The second seeded area 42 minutes after seeding. Note the undersun in the glaciated area and the abrupt wall of cloud along the untreated edge. Portions of the ground were clearly visible near this wall.

Figure 21. The second seeded area 70 minutes after seeding. The area was composed of ice crystals and super-cooled water cloud resembling small cumuli. Large areas of the ground were visible between the clouds.

although it still contained a mixture of water cloud and ice crystals. The seeding aircraft flew across the treated area in both the north to south and east to west directions. By timing the flight across the treated area, it appeared that the treated area, which was originally a rectangle 3.7 x 4.4 km, had grown to a circle roughly 9 to 11 km in diameter. This is a growth in area almost five-fold. The aircraft continued to observe the seeded area for another 30 minutes, during which very little change was observed. The treated area was never completely converted to ice crystals nor cleared out (see Figure 21), although several holes existed through which large areas of the ground could be seen. After 80 minutes of observation, the mission was terminated due to a lack of oxygen.

The concentration of 44 gm $(\text{n mi} - \text{Kft})^{-1}$ used in the second seeding appeared to be adequate to open the area to the point where the ground could be observed from directly above the treated area. If the second seeded area had been correctly sited directionally upwind, it would have opened up in the time interval required to drift over the target (approximately 45 minutes).

FEBRUARY 18, 1977

Target: Roscommon County Airport

Seeding site: Area 298°/18 n mi (33 km) from Roscommon County Airport

Computed winds at cloud top: 300°/22 kts

Weather situation: Weak low at surface and aloft near James Bay. Cold front approaching from northern Michigan and Wisconsin. Upper trough approaching from west with moderate cyclonic flow.

Cloud Data:

Type: Stratocumulus, solid all areas

Height-temperature: Top 6500 ft (1.98 km), -9.5°C
Base ≃ 2500 ft (.76 km) ≃ -3.0°C
Depth ≃ 4000 ft (1.22 km)

Seeding Rate Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: Line, 1 n mi (1.8 km) long

Concentration[1]: 200 to 20 gm (n mi - Kft)$^{-1}$

Output: 24 flares, 480 gm AgI total

Drop altitude: 6300 ft (1.17 km)

Time: 1034 EST

Results:

The response to seeding was again quite rapid. Seven minutes after seeding a glaciated line was evident. By 16 minutes much of the treated area had begun to descend below the main cloud deck with the solid wall of the water cloud clearly in evidence all around the glaciated area. No portion of the ground was visible at this time. Thirty-six minutes after seeding (1110 EST), the seeding aircraft descended into the treated area. The airplane made a visual descent below 1.2 km, but was in the cloud and could not see the ground before reaching the minimum enroute altitude of .82 km. Fifty minutes after seeding, the treated area was a large rectangular shape about 2.3 km wide and about 5.5 km long. The seeded area was tracked for 60 minutes, and during that time it moved on a track more west to east than the original calculation of from 300 degrees. Therefore, it was decided that for the seeding pattern test the seeding site should be located more westward from the target. On the basis of the rate test, it appeared that glaciation occurred rapidly all along the line, suggesting that the lower end of the concentration spectrum used would be sufficient for the pattern test. Accordingly, a concentration of 30 gm (n mi - Kft)$^{-1}$ was selected.

Target: Roscommon County Airport

Seeding site: Area 277°/20 n mi (37 km) from Roscommon County Airport

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1) Two flares did not fire due to malfunction.

Cloud Data:

Type: Stratocumulus

Height-temperature: Top 6000 ft (1.83 km), -8.5°C

Base ≃ 2500 ft (.76 km, ≃ -3.0°C

Depth ≃ 3500 ft (1.07 km)

Seeding Pattern Test Data

Agent: 20-gm AgI pyrotechnic flares

Pattern: 3 parallel lines, each 3 n mi (5.6 km) long; 0.6 n mi (1.1 km) spacing between lines 1 and 2, and 1 n mi (1.8 km) spacing between lines 2 and 3. Total raster size 3 n mi x 1.6 n mi (5.6 km x 3.0 km)

Concentration[1)]: 30 gm (n mi - Kft)$^{-1}$

Output: 19 flares per line (total 57), 1140 gm AgI total

Drop altitude: 6200 ft (1.89 km)

Time: 1150 EST

Results:

The first visual evidence of seeding was 13 minutes after seeding where three glaciated lines were observed. These three lines are clearly evident in Figure 22 taken at 16 minutes after seeding. By 29 minutes (Figure 23), the glaciated areas had grown so that the ridges of water cloud between the seeded lines were very narrow. Ten minutes later, about 85 percent of the treated area had been converted into ice crystals, and portions of the ground were becoming visible through breaks in the clouds near the wall of the untreated cloud. From this point on, the changes in the texture of the treated area were slow. More of the area thinned out as the ice crystals snowed out of the treated area, and more of the ground became visible, but about ten percent of the area remained as water cloud throughout the test. Portions of the shore of Houghton Lake became visible at 48 minutes (Figure 24), and the adjustment in the seeding site paid off as the target (Roscommon County Airport) became visible through breaks and through thin ice crystals at 67 minutes (Figure 25). Communications with ground personnel at the Houghton

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1) Actual concentration was less due to malfunction. See "Results".

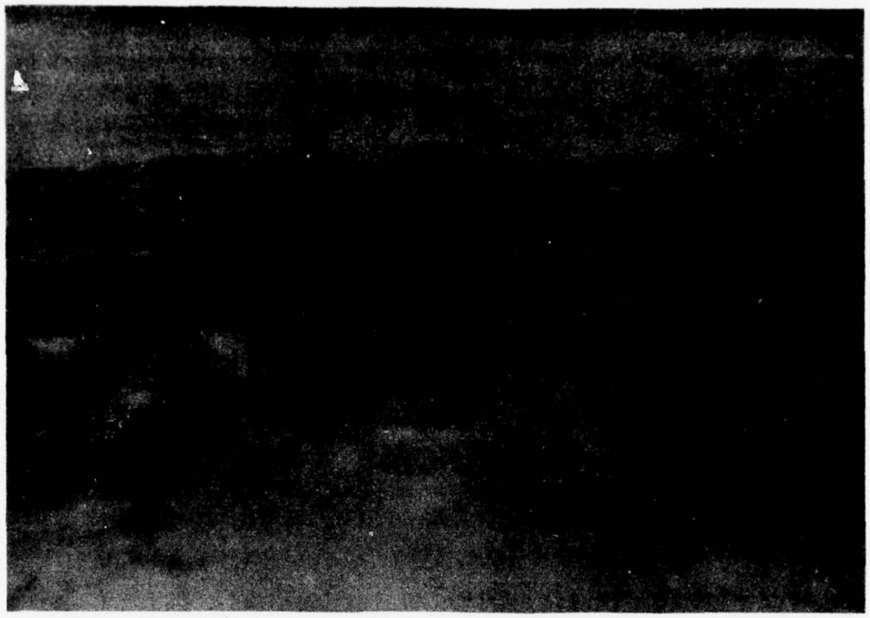

Figure 22. Stratocumulus 16 minutes after seeding in three parallel line pattern. Lines 1 and 2 are closer together in right of picture and line 3 extends vertically near the left edge of the picture.

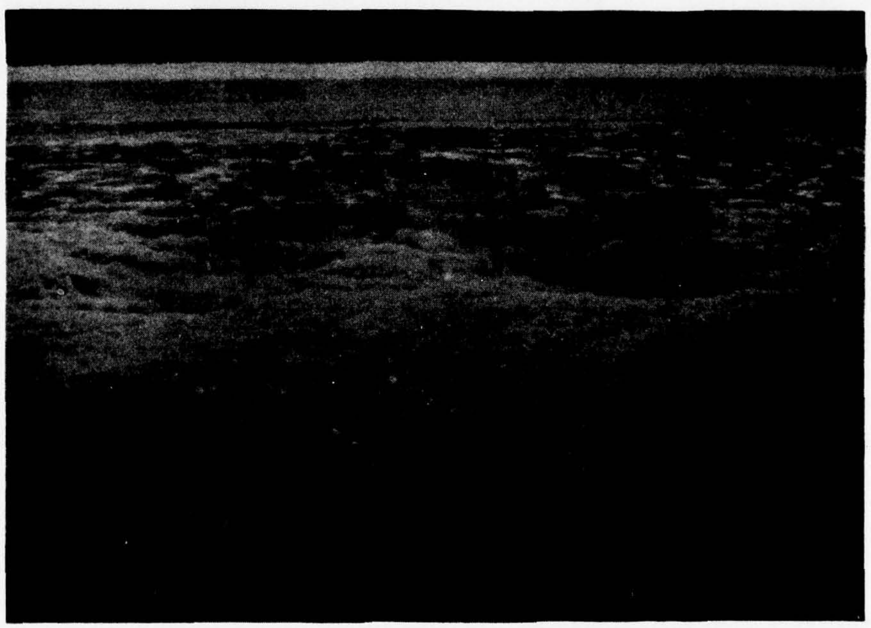

Figure 23. The same seeded area 29 minutes after seeding. Narrow lines of water cloud are still visible between the growing glaciated regions.

Figure 24. A portion of the shoreline of Houghton Lake (ice covered) visible through a hole 48 minutes after seeding.

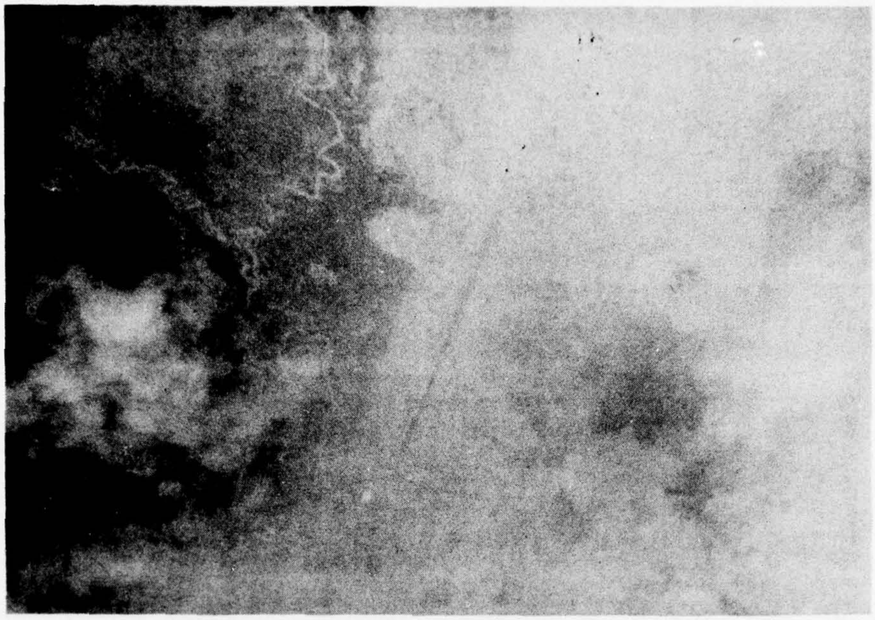

Figure 25. The pre-selected ground target (Roscommon County Airport) is visible as the thin vertical line in the center of the picture 67 minutes after seeding. The seeding occurred 20 nautical miles to the west-northwest of the airport.

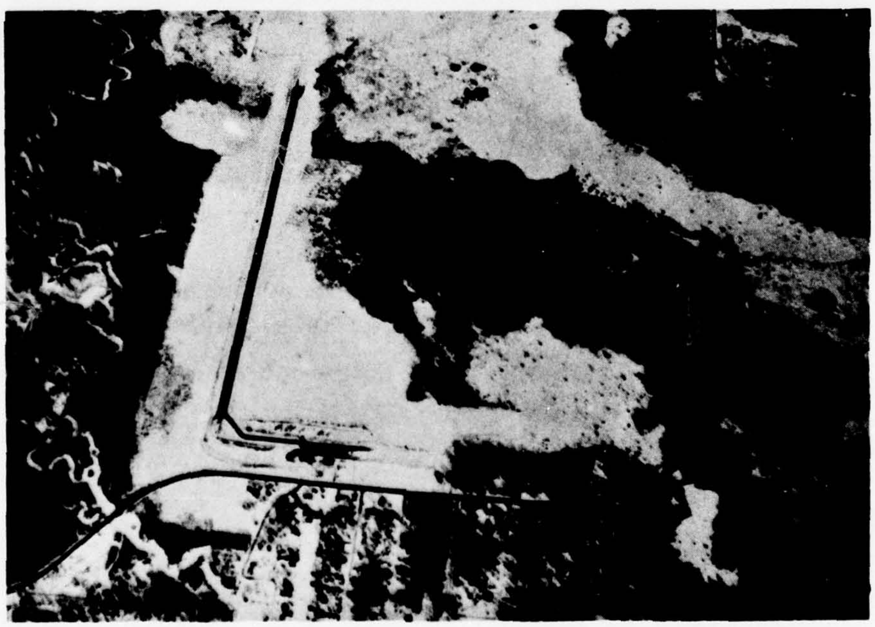

Figure 26. Roscommon County Airport at Houghton Lake, Michigan, taken on a cloudless day from a lower altitude than in Figure 25.

Lake Weather Service Office confirmed that they could see blue sky through the only hole around at that time. It took approximately one hour and seven minutes to reach the target, which would indicate that the treated area moved from 275° at about 20 knots. For comparison, Figure 26 which shows the Roscommon County Airport on a cloudless day is included.

At the time of the test it was anticipated that the concentration of 30 gm $(\text{n mi} - \text{Kft})^{-1}$ would be enough to cause much of the area to clear. Although much of the area did thin out and some breaks did appear, most of the treated area remained covered with ice crystals and some water cloud. Upon landing and inspection of the seeding rack it was determined that a third of the flares that were supposed to have been fired during the raster pattern test did not fire. This was traced to the fact that the basket holding the flares was not bolted tightly to the seeding rack, which in turn caused a poor electrical connection between the rack and some of the flares. In the first seeded line, only 53% of the flares actually fired, while 79% were ignited in line two and 68% were fired in the third line; thus, it would seem that had all of the flares actually fired, it is quite likely that much more of the area would have been cleared out even at the relatively warm temperatures encountered in the cloud deck.

FEBRUARY 19, 1977

Target: Atlanta Airport

Seeding site: Area 330°/10 n mi (18 km) from Atlanta Airport

Computed winds at cloud top: 330°/15 kts

Weather situation: Weak low pressure in southern Ontario with cold front southwest through the Ohio Valley. Cyclonic flow at the surface and aloft with upper trough over Lake Huron and southward.

Cloud Data:

Type: Slightly convective stratocumulus, continuous but undulating with areas of relatively thinner cloud through which the ground could occasionally be seen.

Height-temperature: Top 4500 ft (1.37 km), -12°C

Base 2800 ft (.85 km), -10.5°C

Depth 1700 ft at thickest point (.52 km)

Seeding Rate Test Data:

Agent: 10-gm AgI pyrotechnic flares

Pattern: Line, 2 n mi (3.7 km) long

Concentration: 70 to 7 gm (n mi - Kft)$^{-1}$

Output: 18 flares dispensed, 180 gm AgI total

Drop altitude: 4500 ft (1.37 km)

Time: 1049 EST

Results:

The response to seeding was immediate. Two minutes after seeding the line, those areas where the flares entered the cloud deck were visible as a series of small glaciated spots. By six minutes these had expanded to a continuous line. Eleven minutes after seeding an area of glaciated cloud was visible with some holes in it. The ground was visible through these holes, but there were several other thin areas in the cloud deck through which the ground was visible also. There appeared to be a wave formation in the cloud deck with the clouds taking on the appearance of *parallel lines* with thin, almost clear areas between the lines. The seeded area appeared as a glaciated line oriented almost normal to the natural cloud lines before the area began to clear. At sixteen minutes, the area had developed several large holes with some ice crystals in the center. Unlike most of the other tests, however, the wall area of the untreated cloud surrounding the seeded area was not as well defined. This may have been due to the relative thinness of the cloud deck. Twenty-seven minutes after seeding, the area was tracked on a course of 360° at 8 knots. The area continued to drift on that course and passed 13 km west of the target 50 minutes after the seeding had begun. At that time the cloud conditions were overcast to broken with three large clear areas evident. One of these was the treated area, and one of the other two was located 5.5 km east of the town of Atlanta. The third hole was 11 km south-southwest of Atlanta. The ground was clearly visible through all of these holes. This cloud deck became more broken with the

passing of time and by 1200 EST (about 70 minutes after seeding), several small cumuli were evident with towers building up to 100 to 150 m above the general tops of the clouds.

The results suggest that the concentration was adequate to affect a clearing in the cloud deck. The natural breakup of the clouds into convective stratocumulus and cumulus precluded further tests.

FEBRUARY 22, 1977

Target: Otsego County Airport

Seeding site: Area 235°/6 n mi (11 km) from Otsego County Airport

Computed winds at cloud top: 230°/6 kts

Weather situation: Weak shallow cold front oriented east to west across central lower Michigan. Broad trough aloft above .5 km (2000 ft) over Lake Michigan.

Cloud Data:

Type: Stable stratocumulus, solid all areas with considerable haze above cloud deck to 2 km.

Height-temperature: Top 3700 ft (1.13 km), -6°C
Base 2800 ft (.85 km), -6°C
Depth 900 ft (.27 km)

Seeding Rate Test Data:

Agent: 10-gm AgI pyrotechnic flares

Pattern: Line, 1 n mi (1.8 km) long

Concentration: 200 to 20 gm $(\text{n mi - Kft})^{-1}$

Output: 24 flares dispensed, 240 gm AgI total

Drop altitude: 4500 ft (1.37 km)

Time: 0855 EST

Results:

Response to the seeding was negative. After the seeding drop was made, the seeding aircraft went into the usual holding pattern above the seeded area with the observation aircraft holding above at an altitude of 2.3 km

(8200 ft). Neither aircraft crew observed any evidence of glaciation in the treated area. The area was observed for 45 minutes during which time the cloud deck began to dissipate, but the dissipation appeared to be occurring naturally over the entire region. There was never any evidence of visible ice crystals in the cloud deck. When the cloud deck began to dissipate, the decision was made to fly to another area and attempt a second test. The Houghton Lake area, 65 km south of the Gaylord area, had adequate cloudiness and was selected as a target for the second test.

Target: Roscommon County Airport

Seeding site: Area 270°/12 n mi (22 km) from Roscommon County Airport

Computed winds at cloud top: 270°/15 kts

Cloud Data:

Type: Stable stratocumulus

Height-temperature: Top 4500 ft (1.37 km), -3.0°C

Base 3200 ft (.98 km), -4.0°C

Depth 1300 ft (.40 km)

Seeding Rate Test Data:

Agent: 10-gm AgI pyrotechnic flares

Pattern: Line, 1 n mi (1.8 km) long

Concentration: 200 to 20 gm $(\text{n mi} - \text{Kft})^{-1}$

Output: 24 flares dispensed, total 240 gm AgI

Drop altitude: 4500 ft (1.37 km)

Time: 1004 EST

Results:

The response to seeding was the same as in the previous test, with no visible signs of glaciation and no evidence that any subsequent thin areas or holes were produced by the seeding. At nine minutes and again 26 minutes after seeding, a thinning of the clouds was observed, but no glaciation could be seen. Forty minutes after seeding, the whole cloud mass began to break up generally clearing from north to south. The observed results seemed to fit the pre-test assumptions that cloud decks with a temperature

structure warmer than -7°C would not be receptive to seeding in the concentrations used.

FEBRUARY 26, 1977

Target: None

Seeding site: Area 255°/21 n mi (39 km) from the Sault Saint Marie VOR

Computed winds at cloud top: None

Weather situation: Low pressure over James Bay with weak cyclonic flow at all levels over the Great Lakes region.

Cloud Data:

Type: Thickening stratocumulus

Height-temperature: Top 4200 ft (1.28 km), -14°C
Base 2700 ft (.82 km), -11.5°C
Depth 1500 ft (.46 km)

Seeding Rate Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: Line, 1 n mi (1.8 km) long

Concentration: 90 to 9 gm $(\text{n mi - Kft})^{-1}$

Output: 12 flares dispensed, 240 gm AgI total

Drop altitude: 4500 ft (1.37 km)

Time: 1038 EST

Results:

The response to seeding was not initially observed because the observation aircraft did not have visual contact with the seeding aircraft. The seeded area was first observed as a well-developed glaciated line at 16 minutes after seeding. Twenty-two minutes after seeding, the seeded area had grown to an elliptical shape and was composed of mostly ice crystals with some water cloud near the wall of the untreated cloud. At 1108, or 30 minutes after seeding, the treated area had become almost 7.0 km long and portions of the ground were visible through breaks in the cloud mass. Forty-two minutes after seeding, the treated area had grown in size to about 3.5 km wide with several holes in the cloud deck. A radar fix from the radar at

nearby Kincheloe Air Force Base determined that the treated area had moved at a rate of 12 kts from 305°.

At this point it was decided to attempt a seeding pattern test, applying a multiple line raster with Kincheloe AFB as the target. The rate test indicated that the lower end of the concentration would be sufficient, and the value of 36 gm $(\text{n mi} - \text{Kft})^{-1}$ was determined from the location of best clearing.

Seeding site: Area 305°/9 n mi (16.5 km) from Kincheloe AFB, Michigan
Calculated winds from line drift: 305°/12 kts

Cloud Data:

Type: Thickening stratocumulus and altocumulus/altostratus
Height-temperature: Top 5200 ft (1.52 km), -11°C
Base 2700 ft (.83 km), -11.5°C
Depth 2500 ft (.76 km)

Seeding Pattern Test Data:

Agent: 20-gm AgI pyrotechnic flares
Pattern: 5 parallel lines, each 3 n mi (5.6 km) long, 0.6 n mi (1.1 km) spacing between line 1 and line 2, 0.8 n mi (1.5 km) spacing between line 2 and line 3, 1.0 n mi (1.8 km) spacing between lines 3 and 4, and 1.4 n mi (2.6 km) spacing between line 4 and line 5. Total raster size 3 n mi x 3.8 n mi (5.6 km x 7 km).
Concentration: 36 gm $(\text{n mi} - \text{Kft})^{-1}$
Output: 23 flares each line (total 115), 2300 gm AgI total
Drop altitude: 5000 ft (1.52 km)
Time: 1152 EST

Results:

On the basis of the previous line test, it had been anticipated that a rather rapid response to seeding would be observed. So, when ten minutes passed and no visual effects were noted, the crew in the observation aircraft at 3 km (10,000 ft) became suspicious that something was wrong. Communication with the seeding aircraft, which was orbiting just above the top of the seeded cloud deck at 1.7 km, confirmed that just after the raster

pattern seeding was completed another deck of clouds with a base between 1.7 and 1.8 km moved into the area and was blocking the view of the observation aircraft. This was not evident to the crew of the observation aircraft, but was confirmed when the observation aircraft descended from the 3-km level. The aircraft first went through a thin layer of cloud at 2.4 km and then into a thicker deck with tops at 2.1 km. The base of that deck was at 1.84 km with the top of the original seeded deck below at 1.6 km. It was not possible to visibly see evidence of the effects of seeding because of the restricted visibility in the air space between the upper deck and the lower seeded deck. The observation aircraft did descend to 1.7 km, and at 1230 EST (45 minutes after seeding) it was positioned in a location which would correspond with the expected movement of the seeded area (based on the previous rate test movement). The crew felt that they were in the treated area because the ground was occasionally visible (Figure 27), and the clouds looked different. The crew reported that they could see a mixture of ice crystals and water cloud in the area. The aircraft remained in the treated area circling at 1.8 km between the overcast above and the cloud deck below. This lower deck which was scattered to broken, frequently allowed observation of the ground. At 1252 (60 minutes after seeding) the runway at Kincheloe AFB (Figure 28) was visible through many breaks in the clouds. The aircraft then few southwest, and at a position 7.5 km from the Kincheloe runway, the aircraft flew over a solid deck of clouds with no ground visible. On the basis of flying around within the seeded area, it is estimated that the treated area was approximately a circle 14 to 15 km in diameter at a time about 70 minutes after seeding. The observation aircraft continued flying southwestward between solid layers above and below with the upper deck, breaking off about 18 km southwest of Kincheloe. The lower deck continued solid with a few small breaks in it all the way south to within a few miles of Traverse City.

MARCH 5, 1977

Target: Roscommon County Airport

Seeding site: Area 300°/25 n mi (46 km) from Roscommon County Airport

Computed winds at cloud top: 300°/42 kts

Figure 27. Ground visible through seeded area near Kincheloe AFB, Michigan, February 26, 1977. Picture was taken 50 minutes after seeding from 5900 ft with cloud bases 2700 feet and cloud tops 5200 feet. A second cloud deck based at 6000 feet necessitated the low elevation picture.

Figure 28. The runway and surrounding area at Kincheloe AFB observed through the "hole" and ice crystals created in the seeded area. Picture was taken 58 minutes after seeding.

Weather situation: Moderate low pressure at surface and aloft north of Lake Huron moving eastward. Cyclonic flow all levels.

Cloud Data:

Type: Multi-layered stable stratocumulus and altocumulus/altostratus

Height-temperature: Top 8500 ft (2.6 km), -8.5°C
Base 2300 ft (.70 km), -3°C
Depth[1] 6200 ft (1.9 km)

Seeding Rate Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: Line, 1 n mi (1.8 km) long

Concentration: 300 to 30 g $(\text{n mi - Kft})^{-1}$

Output: 36 flares dispensed, 720 gm AgI total

Drop altitude: 8500 ft (2.6 km)

Time: 1431 EST

Results:

Response to seeding appeared to be rather rapid. Seven minutes after seeding, a glaciated line was evident. By 15 minutes, a definite thinning of the top layer was seen. The seeding flares on-board the aircraft were not designed to treat a cloud deck as thick as this one, and it was not expected that it would clear the entire depth of the cloud. Thirty-five minutes after seeding, the seeding aircraft made a descent into the treated area and was able to descend under VFR to about the 1.5 km level. From that point on the aircraft was in solid cloud and never was able to see any ground features. From on top (at 4 km) it appeared that the seeding had cleared out most of the upper deck and a portion of the lower deck as two distinct cloud decks were visible. From tracking, the seeded area targeting was very good with the seeded area passing over the Roscommon County Airport about 32 minutes after seeding, but the thick cloud deck precluded the opportunity to get

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1) Several layers of cloud existed throughout depth. Only major vertical break noted was between cloud top at 6500 ft (2 km) and next cloud base at 7500 ft (2.3 km).

ground contact. A timed fly-over of the treated area 45 minutes after seeding suggested the treated area had grown in length from the original 1.8 km to about 9 km.

MARCH 6, 1977 (AM)

Target: Roscommon County Airport

Seeded area: Area 304°/14 n mi (26 km) from Roscommon County Airport

Computed winds at cloud top: 300°/22 kts

Weather situation: Upper low near James Bay at surface and aloft with weak cyclonic flow over Great Lakes area.

Cloud Data:

Type: Slightly convective stratocumulus, layered with a few thin (< 500 ft) clear areas between decks.

Height-temperature: Top 6200 ft (1.9 km), -9.0°C
Base 2200 ft (.67 km), -4.5°C
Depth 4000 ft (1.2 km)

Seeding Rate Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: Line, 2 n mi (3.7 km) long

Concentration: 100 to 10 gm $(\text{n mi - Kft})^{-1}$

Output: 24 flares dispensed, 480 gm AgI total

Drop altitude: 6100 ft (1.9 km)

Time: 0935 EST

Results:

The response to seeding was moderately rapid with a glaciated line visible after seven minutes. A timed fly-over of the seeded area along the line at 15 minutes indicated that the glaciated area extended for a distance of 4.4 km. Twenty-three minutes after seeding, the area was a mixture of water cloud and ice crystals, but had not thinned enough so that the ground was visible. At 30 minutes, the seeded area was tracked to a position 20 km from the seeding area on a direction from 294 degrees. The timed fly-over of the area in both directions suggested that its size had grown to 2 km

wide and 5.5 km long. Ten minutes later the seeding aircraft descended into the seeded area and reported being able to see the ground from the 1.5 km level. The ground was not visible from 3.8 km, and the seeded area appeared to contain considerable water cloud through the test. Of interest is the face that, in this rate test seeding run, and on subsequent seeding flights made later on this day, the seeding aircraft reported much heavier icing than during any of the previous operations. While it is true that the seeding aircraft was not always in the cloud deck when making the seeding runs on some of the earlier flights, the subjective feeling is that the cloud deck observed on this day contained higher concentrations of liquid water than did the other cloud decks. Whether this was the major factor in the relatively slow transformation of the water cloud to ice or whether the thickness of the cloud deck was the main cause can only be speculated on at this time. However, if it is assumed that the concentration was adequate for the temperature range within the cloud, there is some case for the high cloud water content being the main cause.

Even though the clearing was slow, the decision was made to perform a pattern test. On the basis of the rate test, a wind correction was made to a direction of 295° and 20 knots speed. Because of the relatively slow clearing observed in the line rate test, the higher concentration, 70 gm (n mi - Kft)$^{-1}$, was selected for the pattern test.

Target: Roscommon County Airport
Seeding site: Area 290°/19 n mi (35 km) from Roscommon County Airport

Cloud Data:

Type: Slightly convective stratocumulus
Height-temperature: Top 6500 ft (1.98 km), -10.0°C
Base 2200 ft (.67 km), -4.5°C
Depth 4300 ft (1.31 km)

Seeding Pattern Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: Three parallel lines, each 3 n mi (5.6 km) long, 0.6 n mi (1.1 km) spacing between lines 1 and 2, and 1.0 n mi (1.8 km) spacing between lines 2 and 3. Total raster size 1.6 n mi x 3 n mi (2.9 km x 5.6 km).

Concentration: 70 gm $(\text{n mi - Kft})^{-1}$

Output: 43 flares per line (total 129), 2580 gm AgI total

Drop altitude: 6500 ft (1.98 km)

Time: 1037 EST

Results:

Response time was similar to the previous line rate test. Ten minutes after seeding, three well-defined glaciated lines were visible. Fifteen minutes after seeding, the glaciated lines within the seeded area had not spread very much. Considerable water cloud was evident between the parallel lines. Five minutes later the same was true (see Figure 29). At thirty minutes, the seeded area had moved a distance of 20 km from 290° and had grown in size to measure about 5.6 km wide and 9.2 km long. At that time it was fairly heavily glaciated, but still contained two ridges of water cloud between the glaciated lines and the ground was not visible. The seeded area drifted over the target 50 minutes after seeding, but the ground was still not visible. The seeding aircraft descended into the seeded area to the 1 km level but could not see the ground. Seventy minutes after seeding the area had moved 11 km southeast of the target and appeared to be filling in again with less glaciation and more water cloud. The area was tracked for another ten minutes, and the ground was occasionally visible through small breaks near the wall of the untreated cloud. It was estimated that only about 60-70% of the area was glaciated. The water cloud in the area tended to develop into small cumulus clouds with small clear areas adjacent to them. It is suggested that a higher concentration should have been used to more effectively seed the cloud deck.

MARCH 6, 1977 (PM)

Target: Roscommon County Airport

Seeding site: Area 290°/27 n mi (50 km) from Roscommon County Airport

Figure 29. Slightly convective stratocumulus 20 minutes after seeding March 6, 1977. Area was seeded with three parallel lines each 4.6 km long with spacing of 1.1 km between line 1 and 2 and 1.8 km between line 2 and 3. Ridges of water cloud between glaciated areas are well defined.

Computed wind from earlier pattern test: 290°/22 kts

Weather situation: As in the morning

Cloud Data:

Type: Slightly convective stratocumulus, solid and continuous.

Height-temperature: Top 6700 ft (2.04 km), -9.5°C
Base 2200 ft (.67 km), -4.5°C
Depth 4500 ft (1.37 km)

Seeding Pattern Test Data:

Agent: 20-gm AgI pyrotechnic flares

Pattern: Four parallel lines, each 3 n mi (5.6 km) long, 0.3 n mi (.6 km) spacing between lines 1 and 2, 0.6 n mi (1.1 km) spacing between line 2 and line 3, and 1.0 n mi (1.8 km) spacing between line 3 and line 4. Total raster size 1.9 n mi x 3 n mi (3.5 km x 5.6 km).

Concentration: 80 gm $(\text{n mi - Kft})^{-1}$

Output: 49 flares each line (total 196), 3920 gm AgI total

Drop altitude: 6500 ft (1.98 km)

Time: 1409 EST

Results:

Response to seeding was rapid. Glaciation was visible before the seeding aircraft had finished the last line of the seeding raster. As noted earlier, the seeding aircraft observed much more rime ice accretion than on other days. This time one inch of ice was accumulated during the seven minutes required to make the seeding raster. Twenty minutes after seeding, the ridge of water cloud between each of the seeded lines was still prominent, but was decreasing markedly. In this 20-minute period, the seeded area had drifted 13 km from a direction of 292° true. Twenty-six minutes after seeding, all of the area had glaciated except for a narrow ridge of water cloud running between the second and third seeded lines. By 35 minutes, the treated area had become very well glaciated, but the ground had not become visible as yet. The glaciated area had descended well below the main cloud deck revealing the solid wall along the edge of the untreated cloud. Sixty minutes after seeding, the treated area was about 90 percent

glaciated and had grown to a large ellipse over 11 km long. The ground was becoming visible in a few places through thin spots in the ice crystals and between breaks in the clouds. Sixty-nine minutes after seeding, portions of the lake shore to the west of the airport were visible, and at 79 minutes, the airport itself became diffusely visible through the ice crystals. The area was too full of ice crystals to allow more than a short glimpse looking straight downward. The oblique view from some distance away was never clear enough to see ground features. Ninety minutes after seeding, a portion of the treated area had moved to the east of the target and had grown to a circular shape almost 18 km across. Several land features such as an interstate highway, and small lakes and streams located east of the airport became clearly visible through large clear areas during this interval. By 100 to 110 minutes after seeding, it appeared that the cloud within the treated area was beginning to fill back in again as the clear areas became smaller and few in number. The area was observed for another ten minutes during which time no noticeable change was observed.

This cloud deck was the same as the one seeded earlier in the day and had essentially the same characteristics. More clearing occurred with the second raster test pattern than with the first one. For the second test, the seeding concentration was increased from 70 to 80 grams, more lines were seeded and the spacing between the lines was slightly reduced. These may all have contributed to the greater success of the second test, but the general feeling is that a significantly greater concentration would have to have been used in that cloud deck to cause it to completely snow out and produce a large clear area.

7. ANALYSIS AND DISCUSSION

7.1 Targeting

These tests suggest that targeting the clearing over a predetermined ground location would be the least troublesome aspect of the problem. In five cases, the clearing drifted over the desired ground target. The misses can be attributed mainly to poor quality wind measurements and, in a few

instances, to faulty navigation. Both of these factors should improve considerably in a tactical situation.

Appendix A describes an analysis of the accuracy required for wind measurements to allow successful targeting. Appendix B describes the wind measurement method used in this study and its expected accuracy. Comparison of the information in these appendices indicate that wind information of significant accuracy is obtainable using this method.

Unfortunately, the autopilot in the seeding aircraft did not function well, so most of the data were obtained from tracks flown manually. The measured winds were compared to the actual drift of the clearings where possible to establish the character of the discrepancies. Table 3 shows the results of this comparison.

TABLE 3. COMPARISON OF MEASURED FLIGHT LEVEL WINDS TO CLEARING DRIFT

Date	Measured Winds	Clearing Drift
2/17	300°/28 kt	290°/20 kt
2/18	300°/22 kt	275°/20 kt
2/19	330°/15 kt	360°/ 8 kt
3/5	300°/42 kt	300°/47 kt
3/6	300°/22 kt	295°/20 kt

The comparisons for March 5th and 6th are considerably better than for the earlier data. This might imply a learning effect on the part of the seeding aircraft flight crew. The propensity for readings of 300° is disturbing and is believed to be due to a misunderstanding of the measurement procedure. In any case, successful targeting was achieved at times with these measurements and a reasonable correspondence is observed.

Another area of concern in targeting is the time required for a clearing to develop. In Figure 30, the time after seeding when the ground was

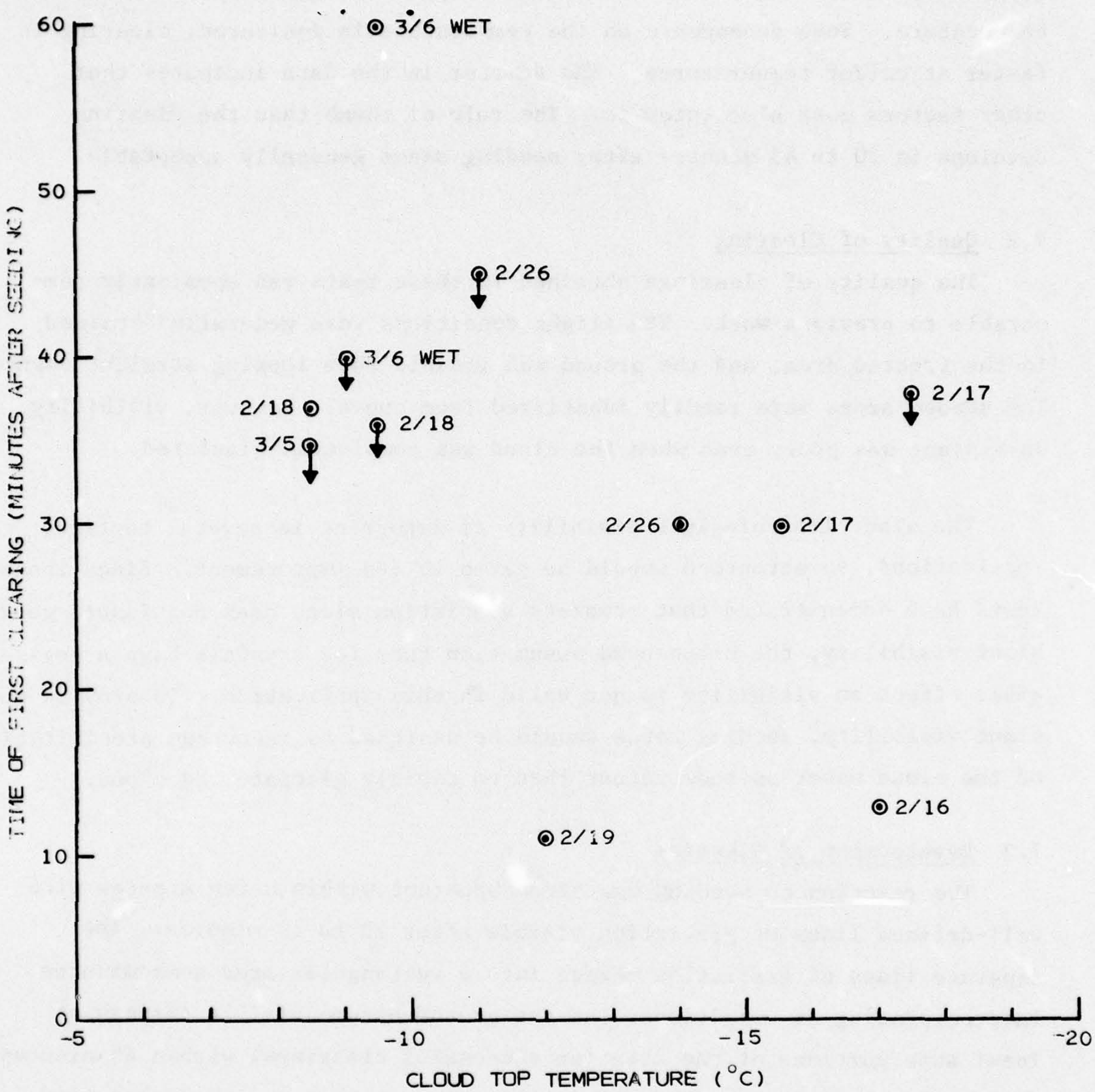

Figure 30. Cloud top temperature versus the elapsed time between seeding and the first observation of the ground through the cloud. The date of the test is entered adjacent to each data point. "WET" indicates the aircraft encountered high icing rates. The downward pointing arrow indicates that time of first clearing may have occurred sooner than plotted.

first observed through the treated area is plotted against the cloud top temperature. Some dependence on the temperature is indicated; clearing is faster at colder temperatures. The scatter in the data indicates that other factors must also enter in. The rule of thumb that the clearing develops in 30 to 45 minutes after seeding seems generally acceptable.

7.2 Quality of Clearing

The quality of clearings obtained in these tests was apparently comparable to previous work. VFR flight conditions were generally obtained in the treated area, and the ground was visible when looking straight down. The seeded areas were readily identified from above. However, visibility on a slant was poor, even when the cloud was completely glaciated.

The slant line-of-sight visibility is important in several tactical applications, so attention should be given to its improvement. Since these tests have demonstrated that complete glaciation alone does not insure good slant visibility, the often-used assumption that ice crystals have a negligible effect on visibility is not valid in this application. To provide good slant visibility, seeding rates should be designed to encourage precipitation of the cloud water as snow rather than to rapidly glaciate the cloud.

7.3 Development of Clearing

The reaction to seeding was often apparent within a few minutes with well-defined lines of glaciation visible after 10 to 15 minutes. The separate lines of glaciation merged into a rectangular area some minutes later, depending on conditions, and the ground became visible through at least some portions of the area (on successful clearings) within 45 minutes. As turbulence dispersed the nuclei, the shape of the glaciated area progressed from a rectangle (or line) to a more elliptical shape to a fairly circular area.

Appendix D contains the outlines of the affected areas as determined from photogrammetric analysis of selected pictures of cloud top. Meteorological conditions prevented analysis of many of the desired photographs, the lack of a well-defined horizon being a common problem. The orientation

of the outlines is determined solely by reference to the outline itself compared to those preceding and following. The orientations are therefore not highly reliable. The apparent shape of the observed area is strongly dependent upon the direction from which the camera is viewing, especially in the cases involving less uniform tops. An example of this is contained in the appendix.

In Figure 31, the length and width of the affected areas have been plotted versus time after seeding for cases in which the photogrammetric data are available. Approximate growth rates were determined for the 20-minute period following seeding using these plots. In Figures 32 through 35, the growth rate is plotted against various parameters which might be expected to correlate. The degree of scatter and small sample size preclude defining relationships among the data.

In Figure 36, the average seeding rates in g $(\text{n mi} - \text{Kft})^{-1}$ for each test have been plotted against the coldest in-cloud temperature. For comparison, three curves have been plotted representing nuclei concentrations of 1.5×10^{14}, 1.5×10^{15}, and 1.5×10^{16} nuclei per nautical mile. These curves are based on the results of the cloud chamber tests. The data points from successful tests will lie on or above the appropriate curve; points from unsuccessful tests will lie below the line. The data show that (at least at temperatures warmer than -13°C) concentrations of nuclei required to produce clearings are significantly less than the expected 1.5×10^{15} g $(\text{n mi})^{-1}$ (comparable to a 4 lb/mi dry ice seeding rate on a 500 m thick deck). This could result from

1) Over-estimates of the nucleation effectiveness of dry ice by Fukuta et al (1971),

2) Under-estimates of the nucleation effectiveness of the silver iodide flares in the CSU cloud chamber tests, or

3) Over-estimates by Vickers and Church (1966) of the required dry ice seeding rates.

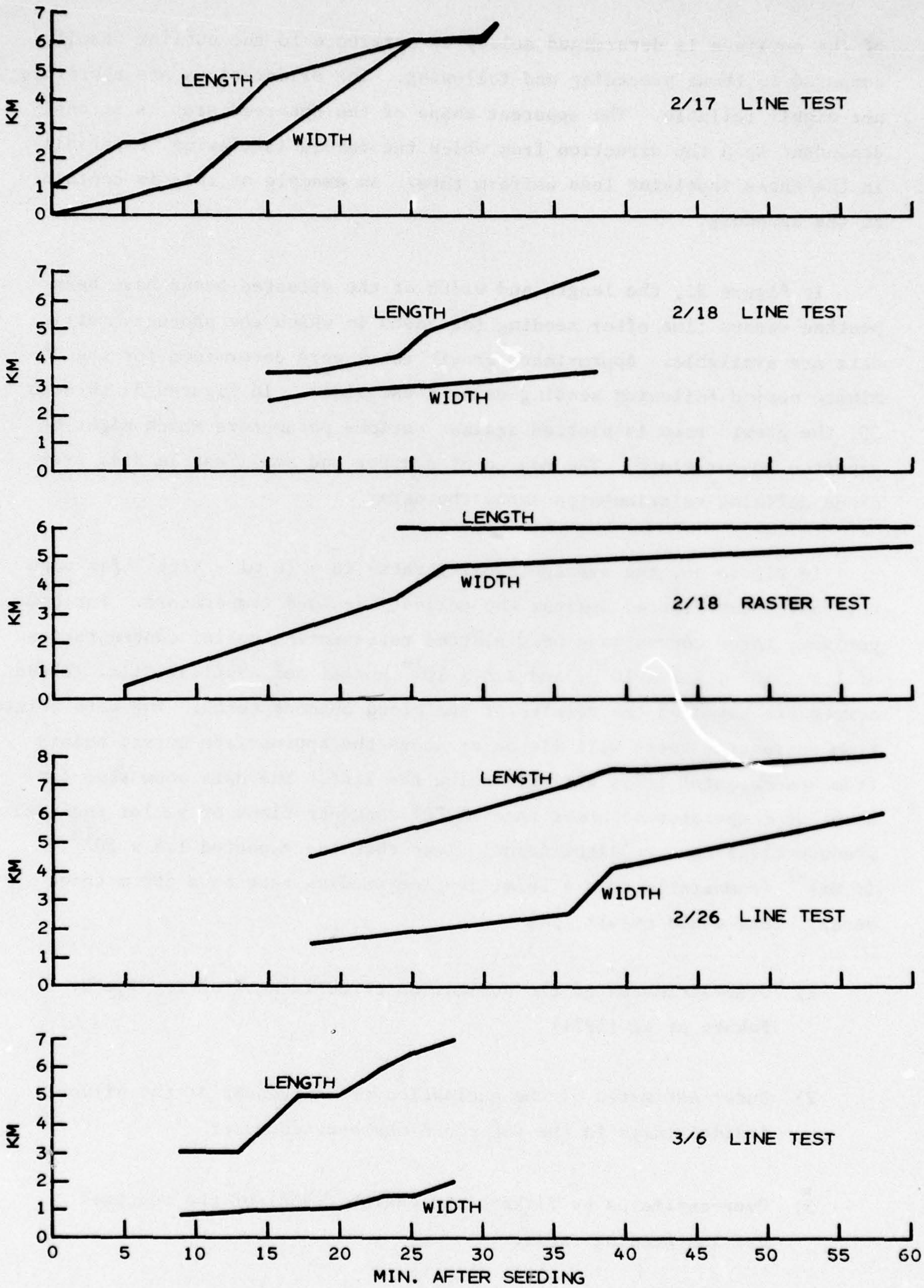

Figure 31. Approximate length and width of the affected area for selected tests using photogrammetric analysis.

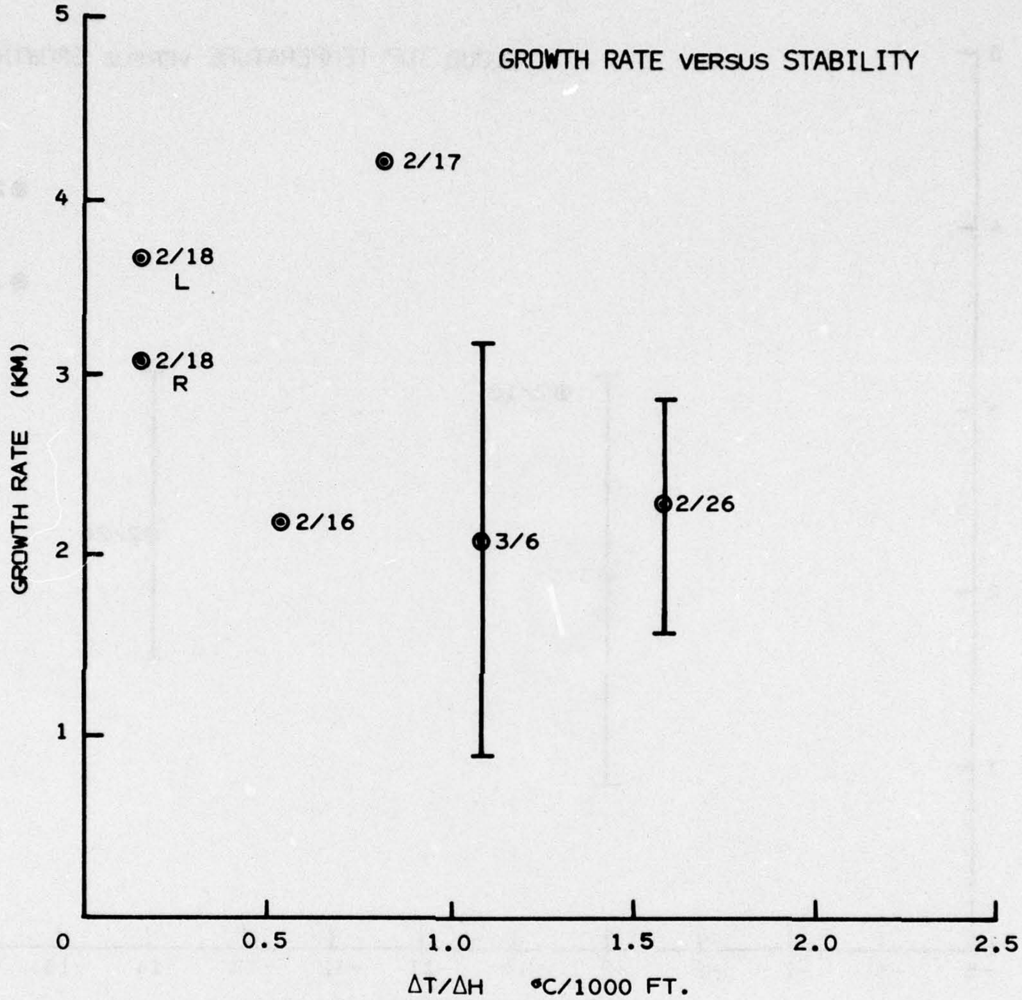

Figure 32. Growth rate of the affected area versus the thermodynamic stability of the area. The vertical lines through the points for 2/26 and 3/6 (Figures 32 through 35) indicate the degree of uncertainty in determination of the growth rate in those cases.

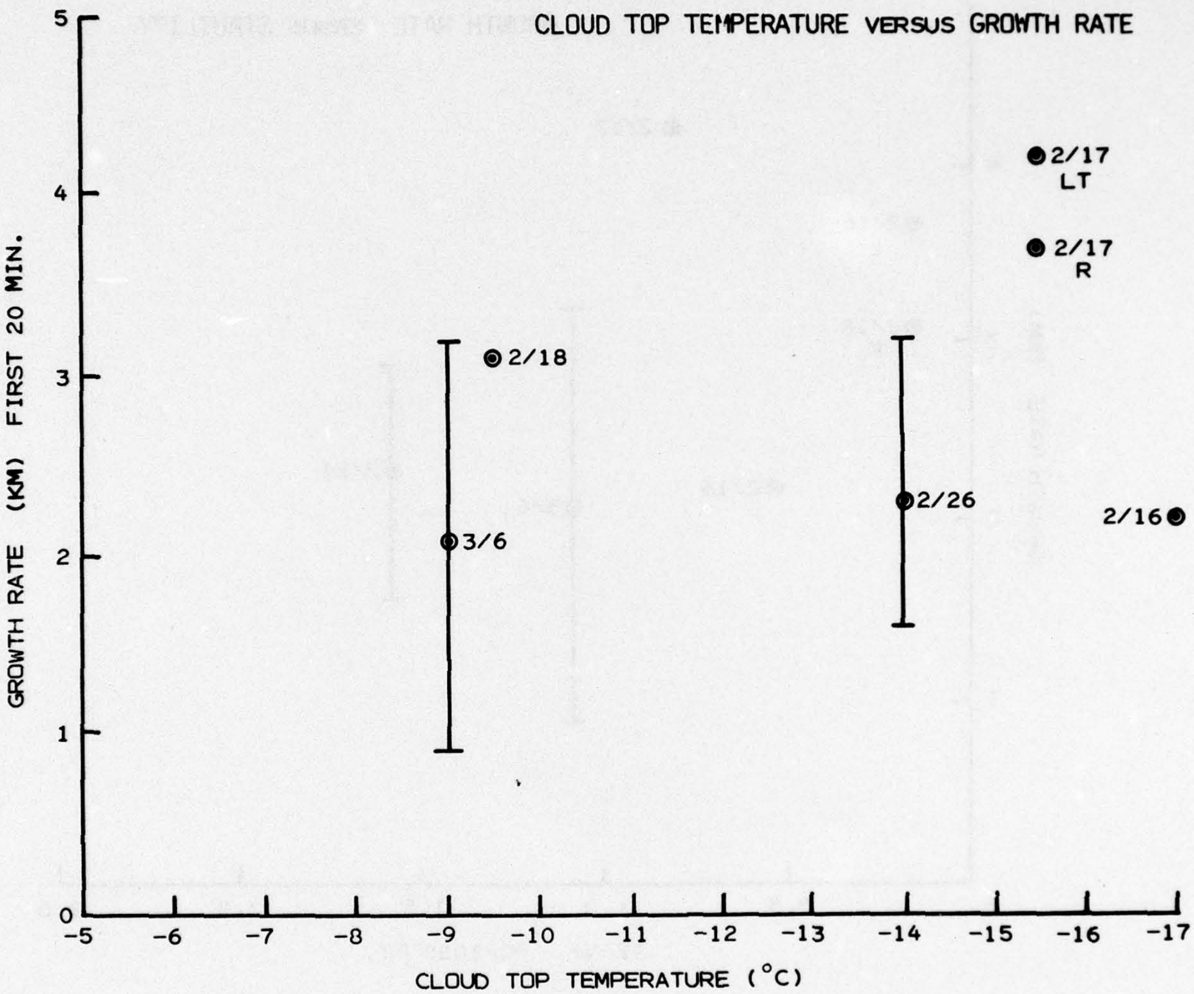

Figure 33. Growth rate of the affected area versus cloud top temperature.

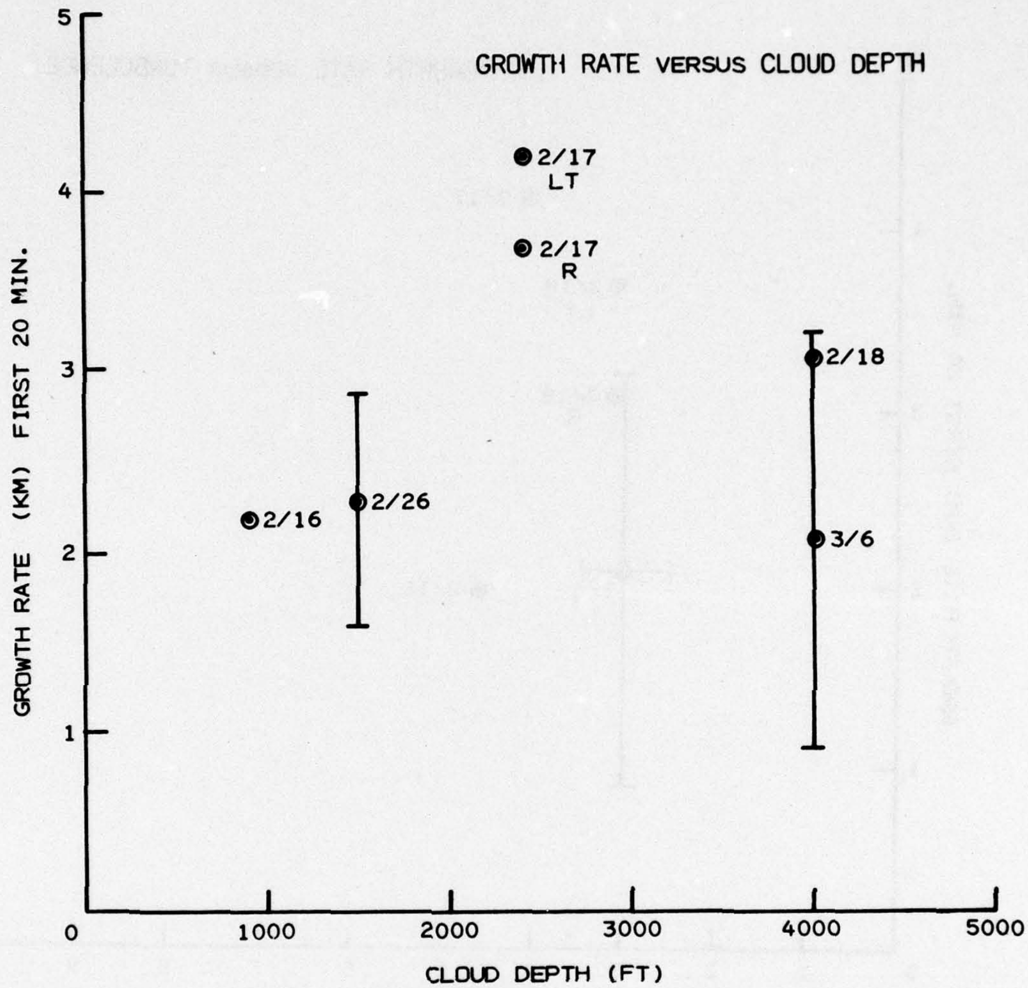

Figure 34. Growth rate of the affected area versus cloud depth.

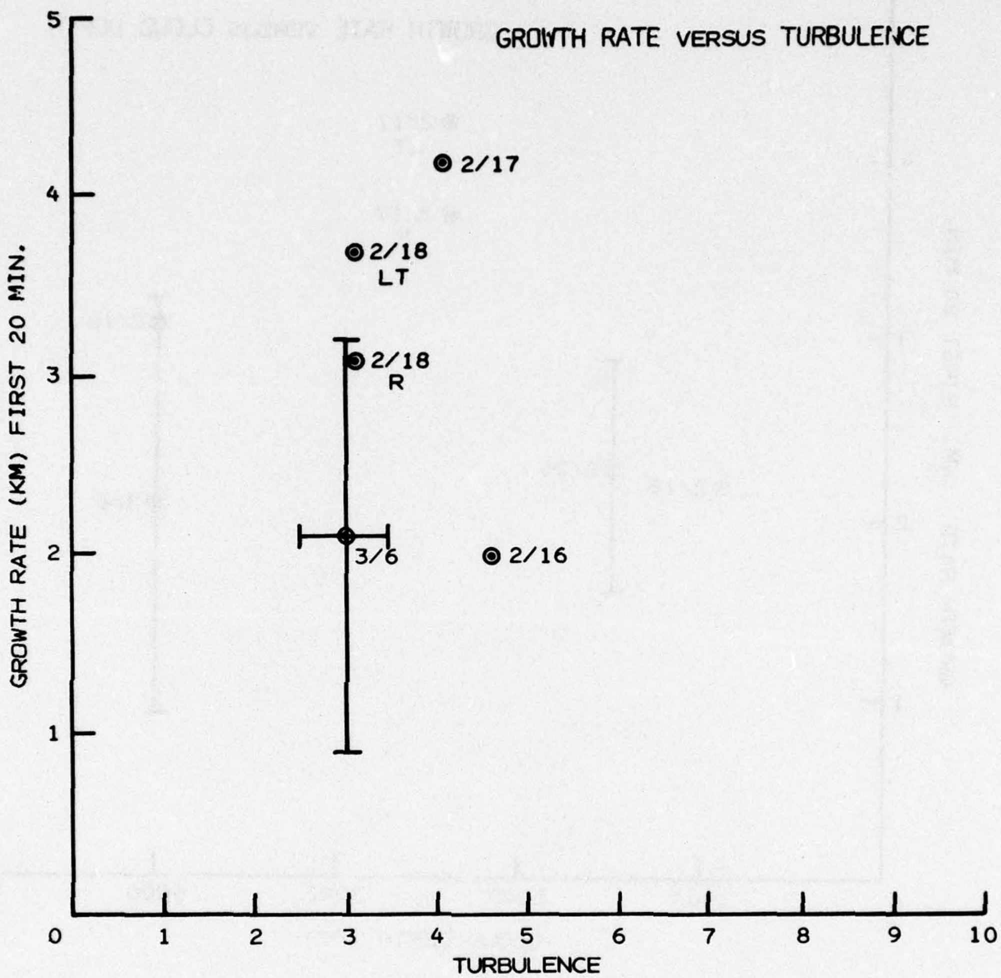

Figure 35. Growth rate of the affected area versus turbulence.

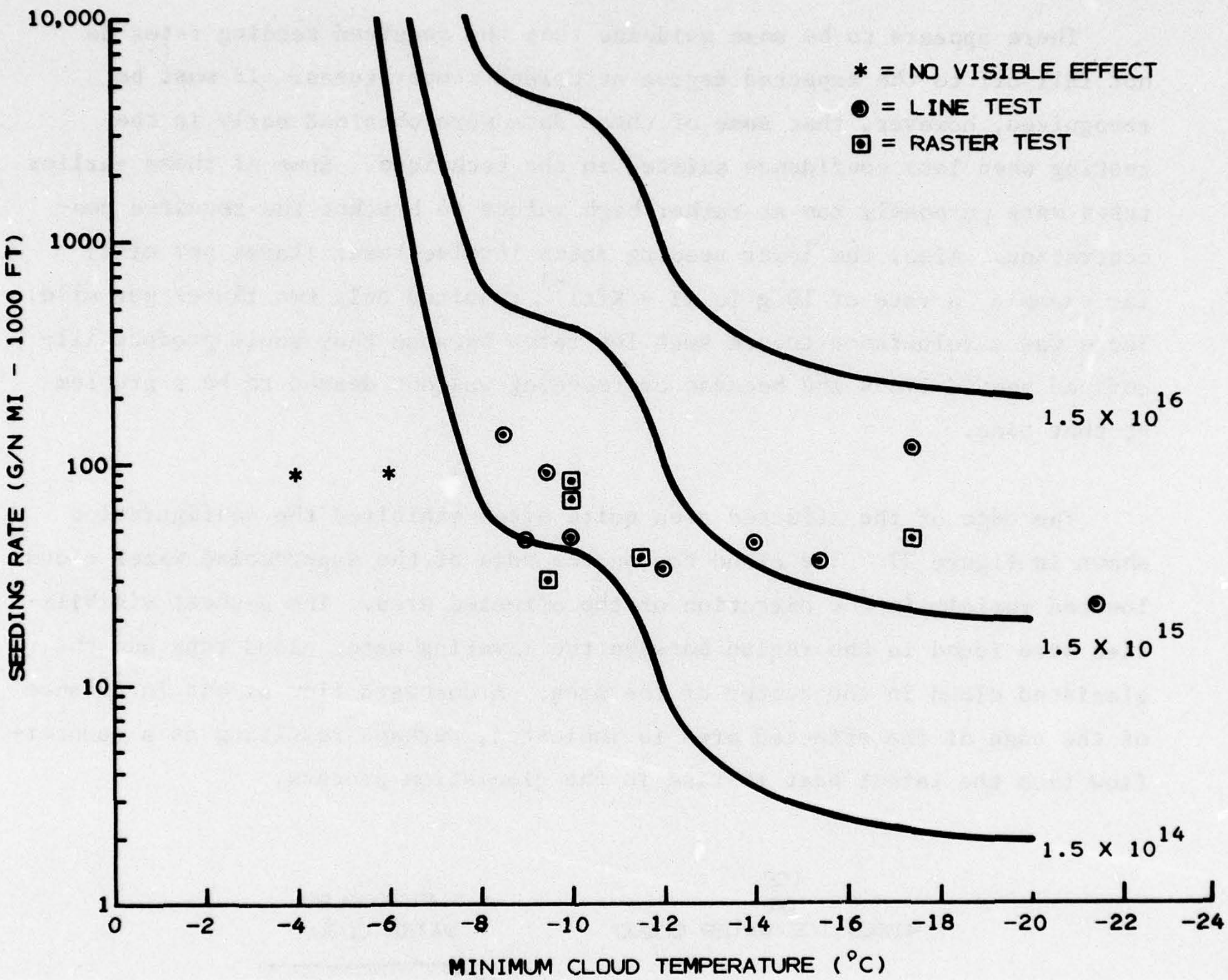

Figure 36. Average seeding rate versus minimum in-cloud temperature. The curves represent calculated nuclei concentrations as described in the text.

The curve for 1.5×10^{14} g (n mi)$^{-1}$ seems to be more representative of the data. This curve is close to the results of the model calculations (Chappell and Smith, 1966), lending some credence to the model results.

There appears to be some evidence that the required seeding rates do not fall off to the expected degree at colder temperatures. It must be recognized, however, that some of these data were obtained early in the testing when less confidence existed in the technique. Some of these earlier tests were purposely run at rather high values to bracket the required concentration. Also, the lower seeding rates involve fewer flares per mile; for example, a rate of 10 g (n mi - Kft)$^{-1}$ required only two flares per mile. There was a reluctance to use such low rates because they would produce ill-defined seeded lines and because overseeding was not deemed to be a problem at that time.

The edge of the affected area quite often exhibited the configuration shown in Figure 37. The cloud top on the edge of the supercooled water cloud lowered rapidly in the direction of the affected area. The highest visibilities were found in the region between the lowering water cloud tops and the glaciated cloud in the center of the area. A downward flow of air in advance of the edge of the affected area is indicated, perhaps resulting as a counterflow from the latent heat release in the glaciation process.

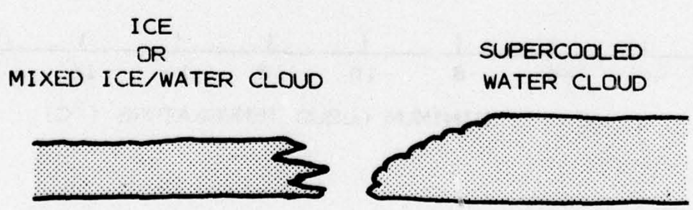

Figure 37. Commonly observed configuration at the edge of the affected area. Since the observations were from above the configuration of cloud base is uncertain.

8. CONCLUSIONS

The major conclusions resulting from this work are stated below. It should be emphasized that those conclusions are based upon a small data sample which somewhat limits the confidence with which they should be interpreted.

- It is possible, using the pyrotechnic flare system, to produce clearings of quality apparently equivalent to those produced by earlier work using dry ice.

- Good visibility vertically downward through the affected area and VFR flying conditions can be produced with some consistency.

- Visibility on a slant line-of-sight through the affected area is not good, often due to ice crystal obscuration.

- Targeting of the cleared area over a specified ground location is not exceptionally difficult.

- It is suggested that the most important meteorological parameter is the coldest in-cloud temperature; successful clearings were obtained with minimum temperatures of -8°C even though temperatures as warm as -3°C were observed within the same cloud. Tests with minimum temperatures of -6°C or warmer failed.

- It is possible to successfully treat stratus decks over 4000 feet thick.

- In some cases, clearings as large as 18 km in diameter can be produced by seeding patterns with dimensions less than 4 km x 6 km.

- It appears that the vertical fall of the seeding device is important in the successful production of clearings in thick cloud decks as evidenced by cases in which clearings were produced to approximately the depth of the seeding device trajectory, but no lower.

9. RECOMMENDATIONS

It appears that a useful tactical system for producing clearings in supercooled stratus decks can be developed. The following recommendations are made regarding efforts to proceed with this development effort.

1. Future field experimentation should include use of an instrumented cloud physics aircraft to allow definition of the physical processes producing the clearing to allow development of techniques to improve the slant visibility through the cleared area.

2. Considerable attention should be given to lowering the seeding rates in an effort to encourage precipitation of the ice crystals rather than complete glaciation. Computer simulation of the clearing mechanisms would be very useful in this regard if the models include the effects of ice crystals on visibilities.

3. Additional work to improve and document the characteristics of the chlorine-doped pyrotechnic seeding formulation should return direct benefits in the form of a more effective nuclei generation system and a better knowledge of the important aspects of the system.

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APPENDIX A

REQUIRED WIND MEASUREMENT ACCURACIES AND THE TARGETING PROBLEM

The primary requirement for accurate targeting of the clearing in a stratus deck is a reliable measurement of the wind speed and direction at various points within the deck. Defining the required accuracy of wind measurements is somewhat problematical. Contributions to measurement error may be from sensor inaccuracy, navigation position error, sampling error (non-uniformity of the wind field in time and space), clearing lead-time misjudgment, and clearing duration variance.

Attempts to define the accuracy required must begin with some assumptions. Figure A1 illustrates the targeting problem in a typical stratus clearing operation. Initially, it is assumed that a rectangular area is seeded directly upwind of the target at a distance sufficient to allow seeding to take effect as the area moves toward the target. The seeding point directly upwind is determined, ideally, by a single wind measurement taken in the stratus layer over the target.

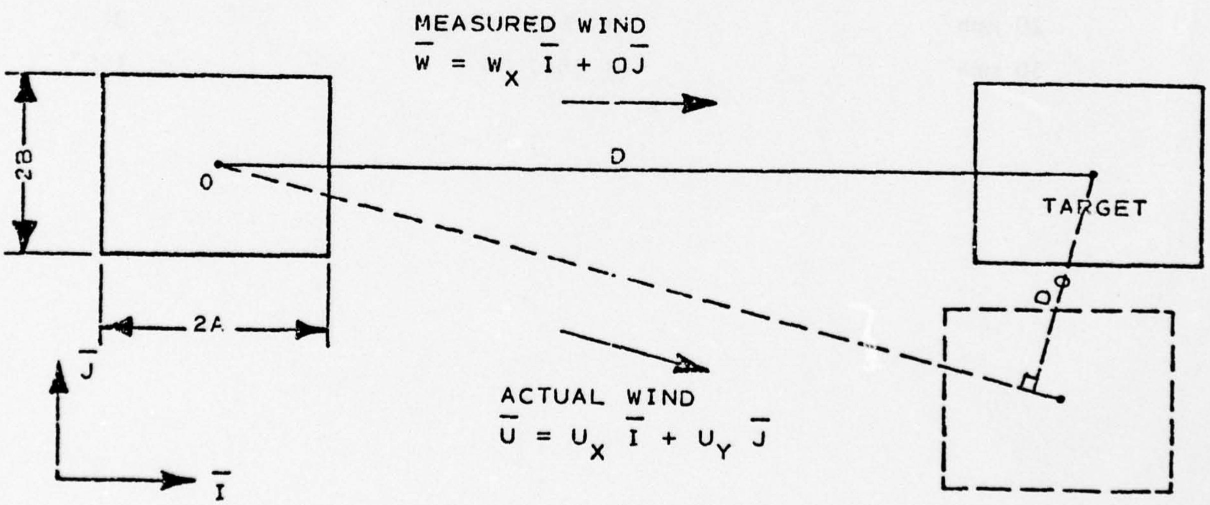

Figure A1. Targeting.

Results of the derivation for a given set of assumptions are listed in Table A1. Wind direction, as expected, must be measured to greater accuracy at higher windspeeds (± 1.5° at 50 mph). This requirement can be relaxed by seeding a wider area at higher windspeeds. The values assumed in the example in Table A1 are the following:

1) Cleared area is square, two miles on a side.

2) Seeding lead-time is 45 minutes.

3) Clearing duration and gestation period are each 30 minutes.

Table A1. REQUIRED WIND MEASUREMENT ACCURACIES

	Allowable Errors	
Actual Speed	Speed (mph)	Direction
2 mph	± 1.4	± 16°
5 mph	± 5.8	± 10°
10 mph	± 3.4	± 6°
20 mph	± 6.7	± 3°
50 mph	± 16.7	± 1.5°

APPENDIX B

MEASUREMENT OF FLIGHT LEVEL WINDS USING GENERAL AVIATION AIRCRAFT

It is possible to make reasonably accurate measurements of flight level winds using aircraft equipped with DME, VOR, and autopilot. Two methods are discussed here. The first uses data from a single straight track flown by the aircraft and requires very accurate heading information. The second uses data from two straight flight tracks and is less sensitive to errors in measurement of heading and airspeed.

Single Pass Method

The aircraft is flown via the autopilot along a VOR radial at constant altitude and airspeed. The following parameters are recorded: VOR bearing, DME ground speed (v_g), true airspeed (v_a), aircraft heading and altitude. For purposes of error analysis, we can assume that the aircraft track will always be due east. In this case the u- and v- components of the flight level wind are

$$u = v_g - v_a \cos \theta$$

$$v = v_a \sin \theta \qquad (1)$$

where θ is the drift angle obtained as the difference between ground track (VOR) and aircraft heading.

Double Pass Method

In this method the aircraft first performs the single pass described above. It then turns around and flies the same radial in the opposite direction (west). All flight parameters (airspeed, altitude, etc.) are maintained constant throughout. Then,

$$u = \frac{1}{2} (v_{g1} - v_{g2})$$

where v_{g1} is the DME ground speed from the first (east) pass and v_{g2} from the second.

The v- component may be determined using either airspeed (v_a) or drift angle (θ)

$$v = \pm v_a \quad 1 - (\frac{v_{g1} + v_{g2}}{2\, v_a})$$

or (2)

$$v = \frac{1}{2} (v_{g1} + v_{g2}) \tan \theta$$

where the sign in the first expression is selected to be the opposite from the sign of θ.

Error Analysis

Given the actual wind speed (w_s), wind direction (ϕ), and airspeed (v_a); we calculate the components

$$u = w_s \sin \phi$$

$$v = w_s \cos \phi$$

the drift angle

$$\theta = \sin^{-1} [\frac{w_s}{v_a} \cos \phi]$$

and the ground speeds for both paths

$$v_{g1} = v_a \cos \theta + u$$

$$v_{g2} = v_a \cos \theta - u$$

The measured quantities (x') are then simulated by adding an assumed error (Δx) to the actual value (x). Thus,

$$\theta' = \theta + \Delta\theta$$

$$v_a' = v_a + \Delta v_a$$

$$v_{g1}' = v_{g1} + \Delta v_{g1}$$

$$v_{g2}' = v_{g2} + \Delta v_{g2}$$

The measured values of the wind components (u' and v') are then calculated by substituting the simulated measured values in equations (1) and (2). Thus, we have three modes of calculation:

A. Single Pass Method.

B. Double Pass Method using airspeed.

C. Double Pass Method using drift angle.

So choosing a set of conditions (w_s, ϕ, v_a) and instrument errors (θ, Δv_a, Δv_{g1}, Δv_{g2}), we can evaluate the resulting error in the measured wind. We define the measurement error as the magnitude of the vetor difference between the actual and measured winds. The error is a function of wind direction; so to obtain a representative value, we calculate the error for all directions and use the maximum error. The signs of the measurement errors ($\Delta\theta$, Δv_a, Δv_{g1}, Δv_{g2}) must also be taken in all possible configurations to obtain a maximum resultant error.

<u>Instrument Accuracies</u>

<u>VOR</u>: The FAA specifies that the maximum error for the entire system, including ground-based transmitter and airborne receiver, shall be no greater than $\pm$ 1°.

DME: The ground speed indicated by the DME is accurate to within $\pm$ 0.1 kt on a well-maintained instrument. Since the measurement actually applies to the slant range, a correction should be introduced based on altitude to obtain true ground speed. The correction process would not introduce significant additional error.

Airspeed: Two errors are of concern in the measurement of indicated airspeed:

1. Installation error - caused by the peculiarities of the pitot-static system on a given aircraft. This error is calibrated by the aircraft manufacturer as a function of indicated airspeed. Using the manufacturer's calibration, this error can easily be corrected to within $\pm$ 1 kt. Selecting the airspeed associated with minimum error ($\simeq$ 140 kt for the Aztec) can reduce this error even further.

2. Instrument error - caused by the error of the airspeed indicator in associating ideal pitot-static pressures with the correct airspeeds. In the lower speed ranges (e.g., 140 kt on the Aztec), this error is within $\pm$ 2 kt. At higher speeds it can approach $\pm$ 3 kt.

Combining the two sources of error, we obtain $\pm$ 3 kt as representative of the indicated airspeed. The correction to true airspeed (based on altitude and temperature) will not add significantly to this error.

Aircraft Heading: In the single pass method, the accurate measurement of absolute heading is crucial, and the common directional gyro system will not suffice. Sufficient accuracy can be obtained, however, by using a gyrosyn compass system often found in the more expensive general aviation aircraft. This system uses a flux gate sensing device mounted on the wing tip (to avoid the magnetic disturbance of the engines) to determine magnetic north. The readout is via a directional gyro system in the cockpit which is slaved to the remote indicator during level flight. When the aircraft altitude departs

significantly from level flight, the gyro is unslaved and acts as a common directional gyro until level flight is re-established. Such systems are accurate to ± 1° in level flight.

In the double pass method, only the relative heading error between the two paths is of importance; absolute error is not important. So a common directional gyro system will suffice. Considering that airspeed is held constant, the drift angles on the two passes will be of equal magnitude and opposite direction. An error which is constant between the two passes will cancel out if the magnitudes of the drift angles are averaged. The FAA requires directional gyros to drift no more than ± 3° in 15 minutes. Assuming no more than five minutes required to complete both passes, the relative error between the two could be as much as ± 1°. In the averaging process, the error in drift angle is reduced to ± 1/2°.

Error Simulations

In order to evaluate the magnitude of the measurement errors, a computer simulation was performed. The airspeed was taken as 140 kts, and various wind speeds from 5 to 70 kts were used. Each case was investigated for all wind directions and all combinations of signs of the instrument errors. The instrument errors used were:

$$\Delta\theta = \pm 1^\circ$$

$$\Delta v_a = \pm 3 \text{ kt}$$

$$\Delta v_g = \pm 0.1 \text{ kt}$$

The measurement errors (as defined previously) were found to be within 4 kts for the single pass method. The measurement errors for the double pass method were within 2.5 kts for wind speeds under 40 kts, increasing to 2.9 kts as the wind speed approached 70 kts. The double pass method using airspeed was found unacceptable, so only the method using drift angle is considered.

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APPENDIX C

PHOTOGRAMMETRIC ANALYSIS TECHNIQUE

The following instructions describe a technique for constructing a perspective grid on an aerial photograph of stratiform cloud of uniform height. The grid then allows the size of features seen in the photo to be estimated fairly accurately.

The method is taken from the Manual of Photogrammetry, Second Edition, Washington, D. C., American Society of Photogrammetry, 1952, 876 pp. The method was initially developed by the Canadian Topographical Society and published in their Topographical Survey Bulletin 62, 1932.

The method requires a photograph of high quality which includes the horizon. The focal length of the lens, the altitude of the aircraft, and the altitude of cloud top must all be known. For best results, 1) the photograph should be of high contrast, 2) the horizon should be well defined, and 3) the features of interest should be as much in the foreground as possible.

1. Lay a piece of acetate of dimensions two or three inches greater than the photograph, glossy side up, on the work surface. Place the photograph face down on the acetate leaving at least a two-inch margin on all sides. Tape the picture securely to the acetate insuring that both are flat. Turn the acetate over so the picture is face up underneath the acetate.

2. Enter on the worksheet 1) project name, 2) date, 3) time, 4) picture number, 5) roll number, 6) aircraft altitude, 7) cloud top altitude, 8) focal length of the lens, 9) width of negative.

3. Locate the principal point (center of the picture) by drawing light construction lines connecting opposite corners of the picture. Be sure to use

the corners of the photographic image, not the corners of the paper. Draw a small circle around the intersection of these lines to designate the principal point.

4. Carefully measure the width of the photograph and enter it on the worksheet. Calculate the effective focal length according to the equation

$$f = (\text{focal length of lens}) \times (\text{width of photo})/(\text{width of negative})$$

Enter f on the worksheet.

5. Draw the apparent horizon line and the principal line. Referring to Figure C1, the apparent horizon is the image of the apparent junction of the cloud deck and the sky. The apparent horizon <u>line</u> is the straight line that is tangent to the curved horizon line in the photograph and equidistant from the curved horizon line at points equidistant from the principal line. The principal line passes through the principal point and is perpendicular to the apparent horizon line. Extend the principal line off the bottom of the picture.

6. Measure the distance h'p from the principal point to the apparent horizon line. Enter it on the worksheet.

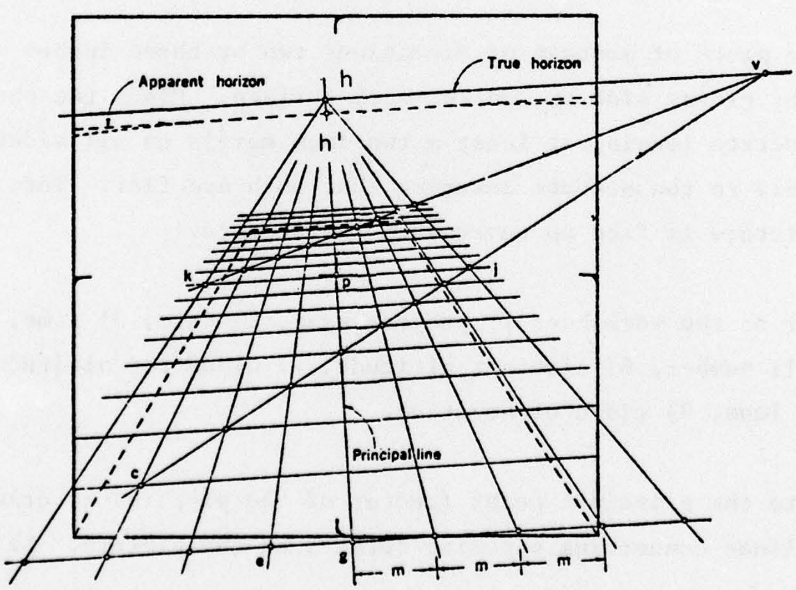

Figure C1. Construction of the perspective (Canadian) grid.

6. Measure the distance h'p from the principal point to the apparent horizon line. Enter it on the worksheet.

7. Calculate the apparent depression angle θ' according to

$$\theta' = \tan^{-1}(h'p/f)$$

and record it on the worksheet. This is the apparent tilt of the camera below the horizontal plane.

8. Calculate H = (aircraft altitude) - (altitude of cloud top). Record on the worksheet.

9. Calculate the true depression angle

$$\theta = \theta' + 0.02959\sqrt{H}$$

where θ and θ' are in degrees and H is in meters. Enter θ on the worksheet. This corrects θ' for the effects of the earth's curvature and atmospheric refraction.

10. Calculate the distance ph from the principal point to the true horizon line according to

$$ph = f \tan \theta$$

Record ph on the worksheet and draw the true horizon line parallel to the apparent horizon line at the distance ph from the principal point.

11. Select a convenient interval M for the imaginary cloud top grid and record on the worksheet. An interval of 1 km is generally acceptable. Record M on the worksheet.

12. Select a convenient interval m to be laid off on the line ge. The value of m should be some even division of a scale such that the point g (Step 13) will lie about at the lower edge of the photograph. If g is closer to p

than the edge of the photograph, some inaccuracy may result; if g is very far below the edge of the photograph, the drafting operations are somewhat unwieldy. Record m on the worksheet.

13. Compute the distance hg from the relation

$$hg = mH/(M \cos \theta)$$

and record hg on the worksheet.

14. Plot the point g on the principal line, construct the line ge parallel to the horizon line, and lay off the intervals m on the line ge both to the right and left of g. The intervals may be accurately laid off by laying a scale on the line and marking the appropriate points opposite the divisions of the scale, whereas to lay off the intervals with a pair of dividers is apt to result in accumulation of error.

15. Draw a line from each interval mark like e to the point h.

16. Compute the distance hv from the relation

$$hv = f/\cos \theta$$

Record hv on the worksheet. Plot the location of the point v on the true horizon line to the right of h.

17. Construct a random straight line vc diagonally across the photograph. It is usually convenient to draw vc approxiately to the opposite lower corner of the photograph.

18. Construct lines parallel to the horizon line through each intersection of the line vc with the lines drawn in Step 15. If more lines are desired above the point like j, construct another line vk to a grid intersection at the opposite end of the last transverse line. Then more transverse lines can be constructed through the intersections of vk with the longitudinal lines (from Step 15).

19. This completes the construction of the perspective grid. The lines forming the grid should be darkened for ease of viewing.

20. Attach the worksheet to the acetate. A sample worksheet is shown in Figure C2.

PROJECT: ____________________

DATE: ____________________

TIME: ____________________

PICTURE #: ____________________

ROLL #: ____________________

AIRCRAFT ALTITUDE: ________________

CLOUD TOP ALTITUDE: ________________

FOCAL LENGTH OF LENS: ________________

WIDTH OF NEGATIVE: ________________

WIDTH OF PRINT: ________________

EFFECTIVE FOCAL LENGTH, F = ________

DISTANCE H'P = ________

APPARENT DEPRESSION ANGLE

$\theta' = \tan^{-1}(H'P/F)$

θ' = ____________

H = (AIRCRAFT ALTITUDE) - (ALTITUDE OF CLOUD TOP)

H = ________________

TRUE DEPRESSION ANGLE

$\theta = \theta' + .02959\sqrt{H}$

θ = ____________

$PH = F \tan\theta$

PH = ________________

SELECTED INTERVAL (M) = ____________

GRID SIZE (m) = ____________

$HG = mH/(M\cos\theta)$

HG = __________

$HV = F/\cos\theta$

HV = ________

COMMENTS: ____

Figure C2. Sample worksheet.

APPENDIX D

PHOTOGRAMMETRIC DATA

This appendix contains the results of photogrammetric analysis of selected tests. The tests were selected on the basis of availability of a significant time series of high quality photographs. In several cases it was difficult to obtain good photographs for analysis because of a poorly defined horizon, poor visibility, or multiple cloud decks.

The orientation of the outlines of the affected areas is determined solely by reference to the clearing features and may, therefore, be in error at times.

The dependence of the analysis method on a uniform cloud top is illustrated by the outlines for T = 23, 25, and 28 minutes in the line test on March 6. The main differences in these outlines are attributable to variations in camera angle.

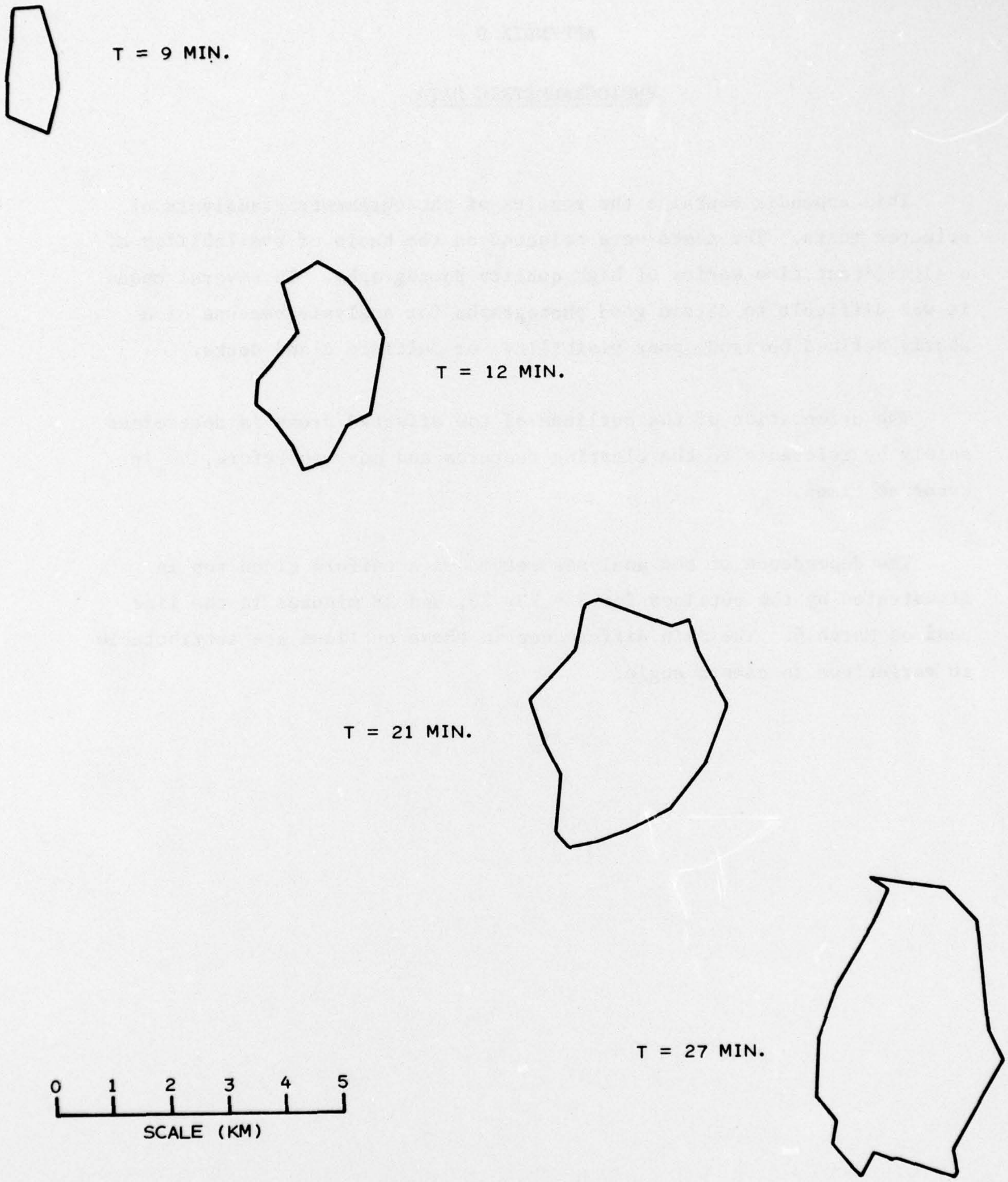

Figure D-1. Line test, February 16.

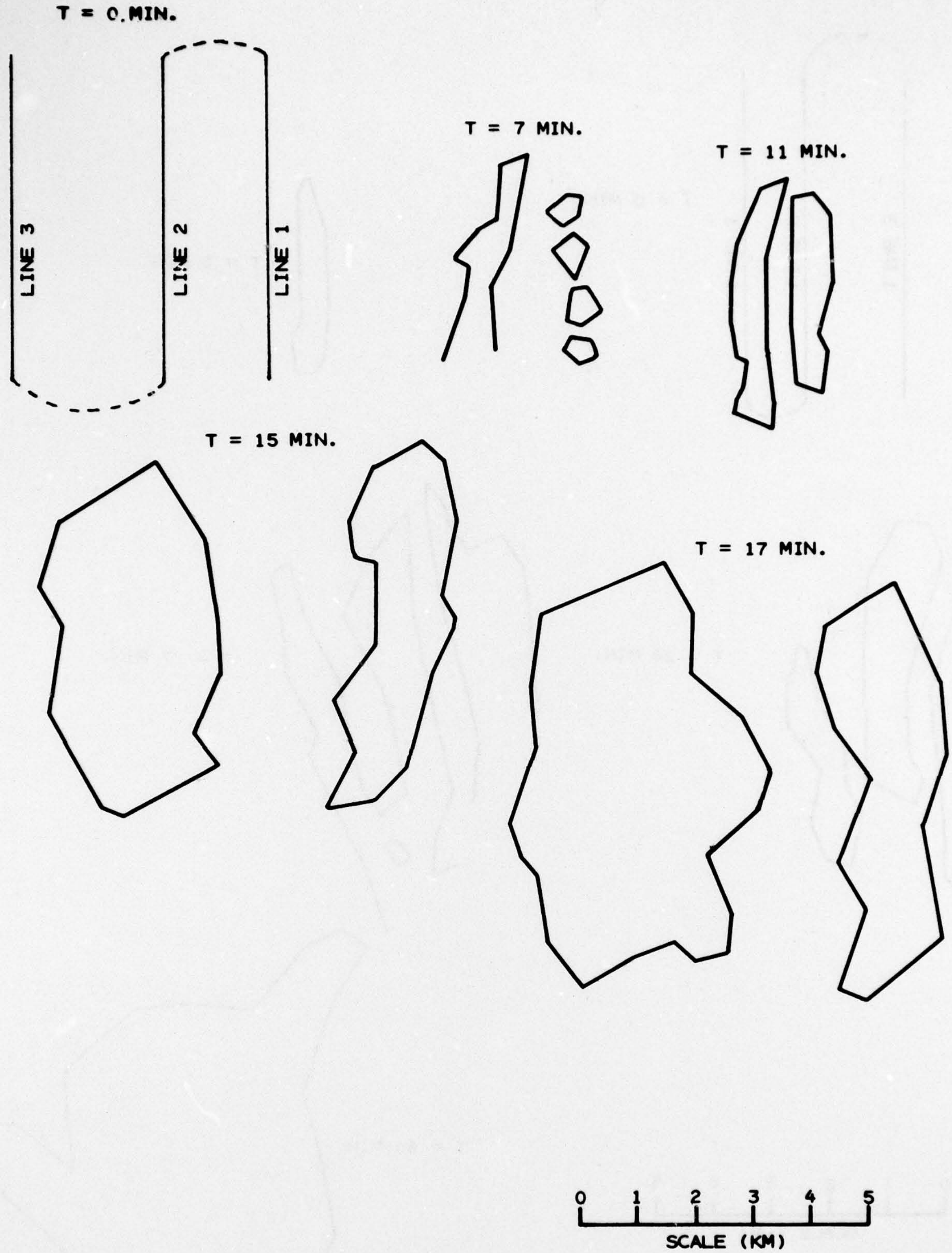

Figure D-2. Raster test, February 17.

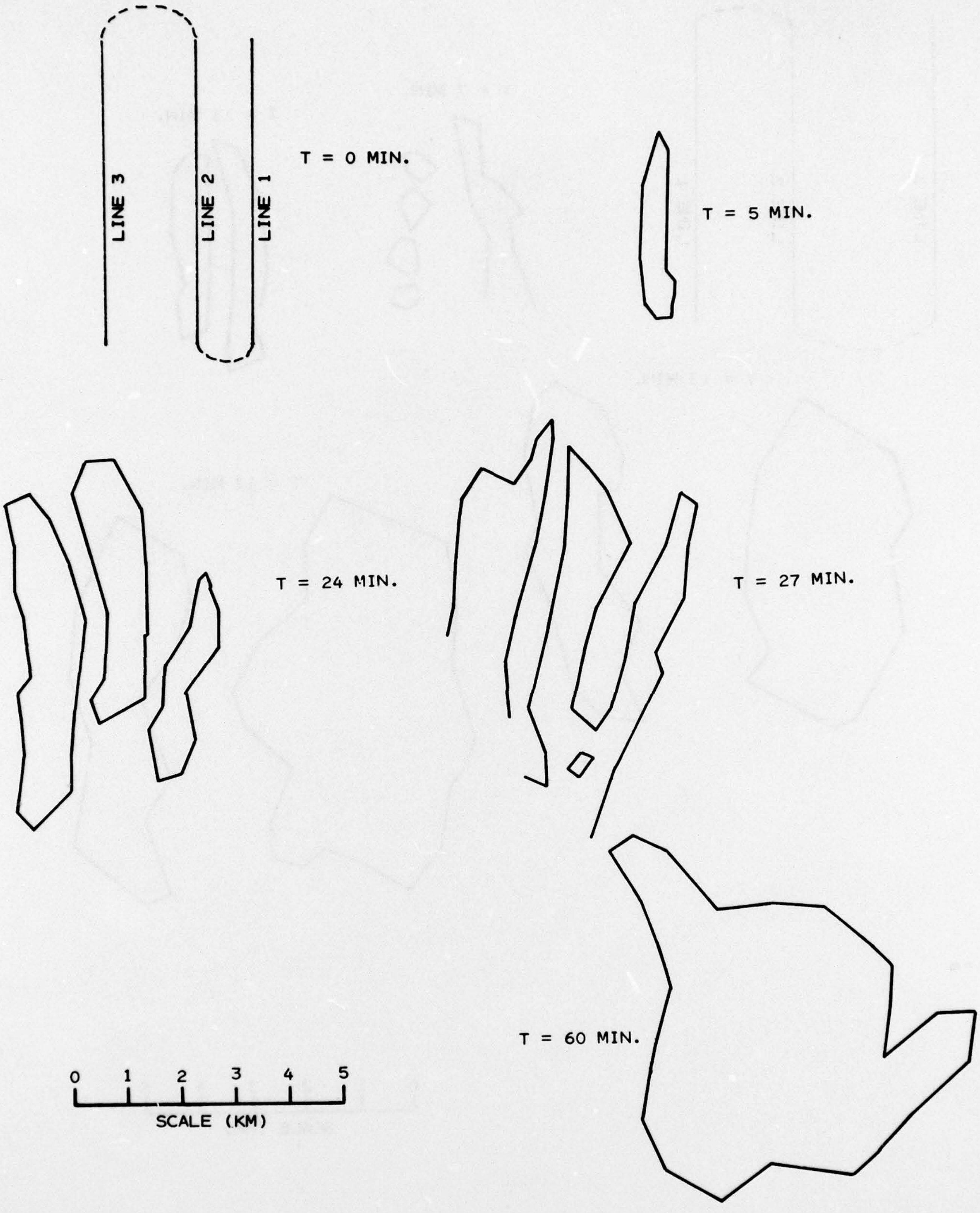

Figure D-3. Raster test, February 18.

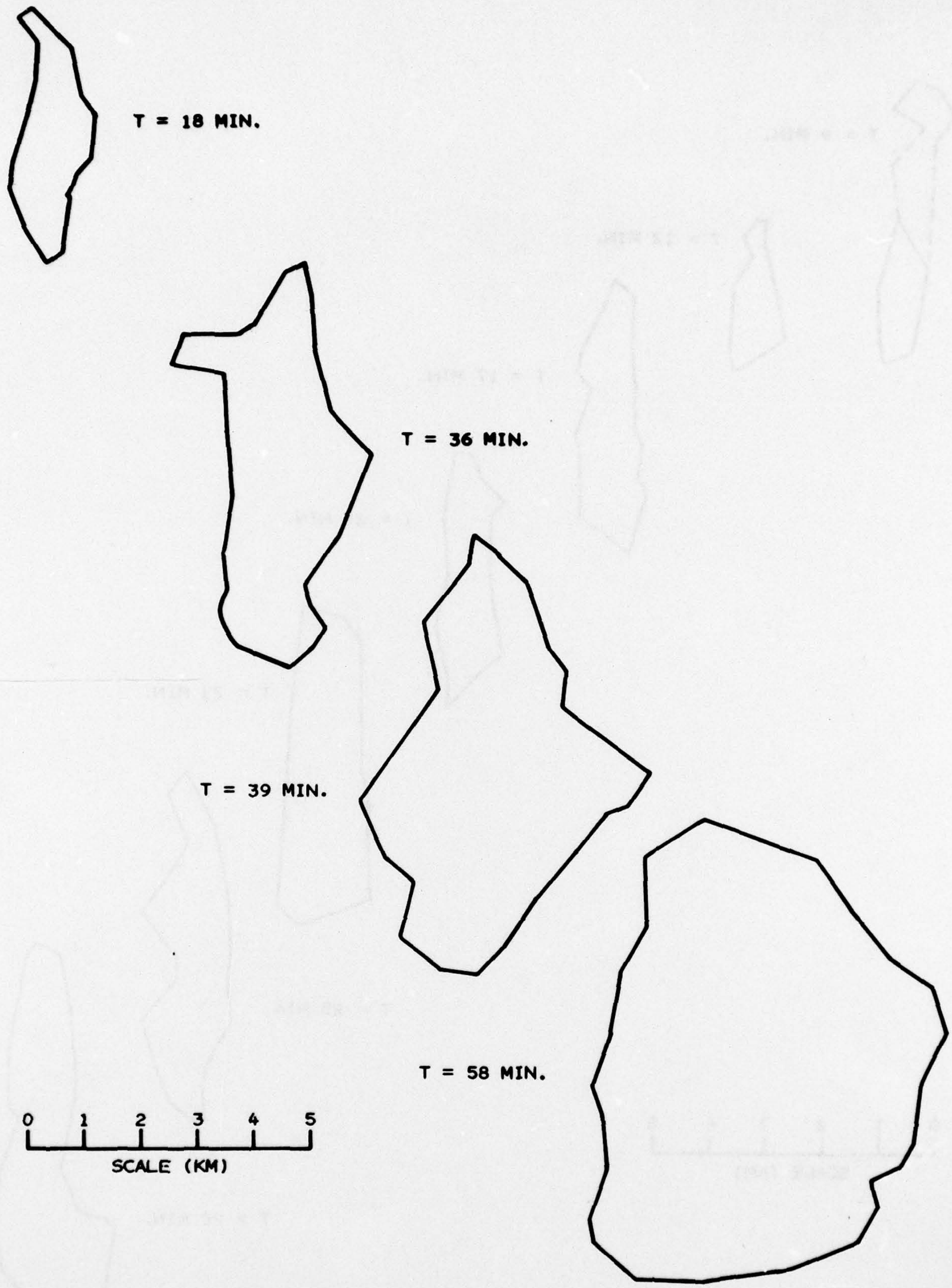

Figure D-4. Line test, February 26.

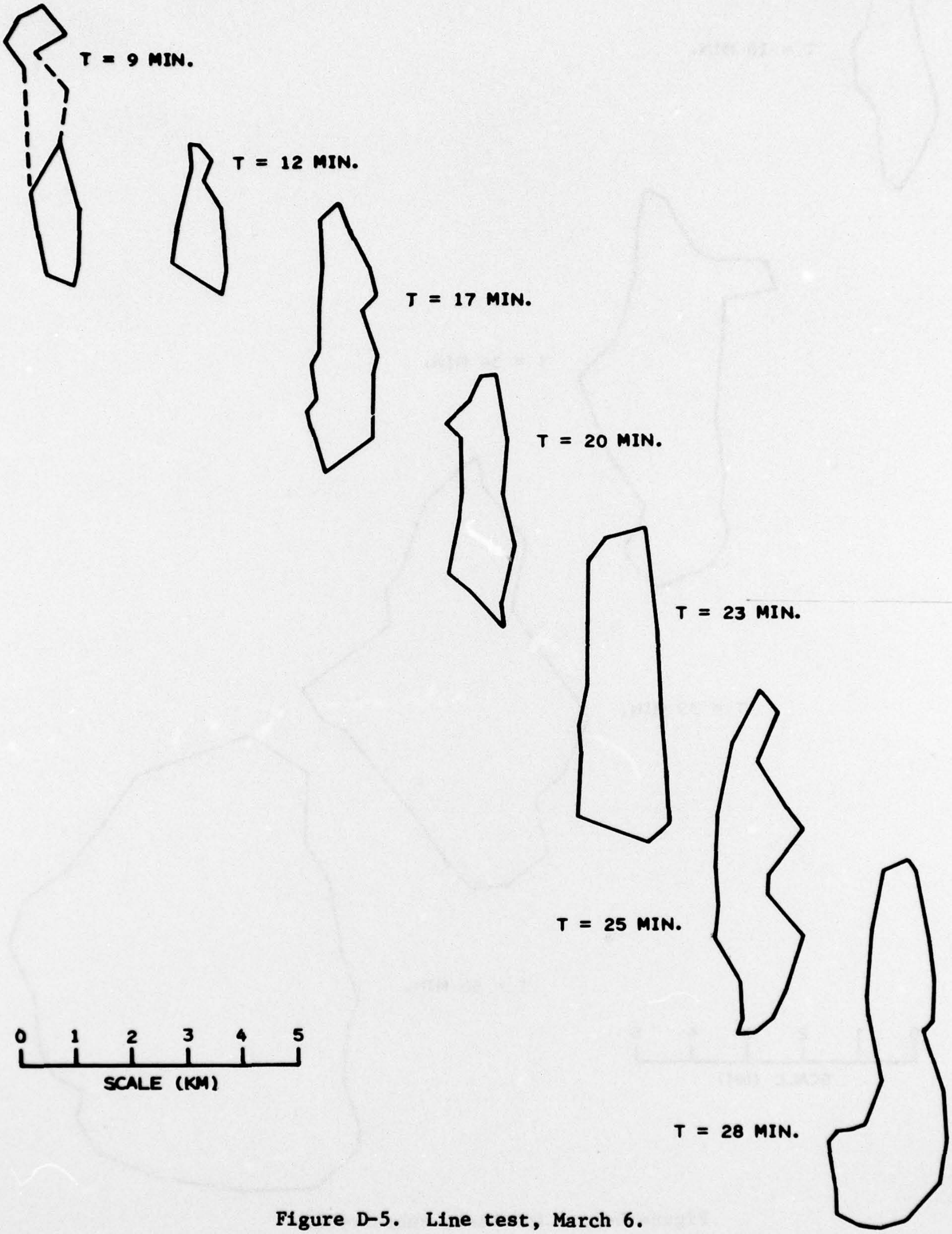

Figure D-5. Line test, March 6.

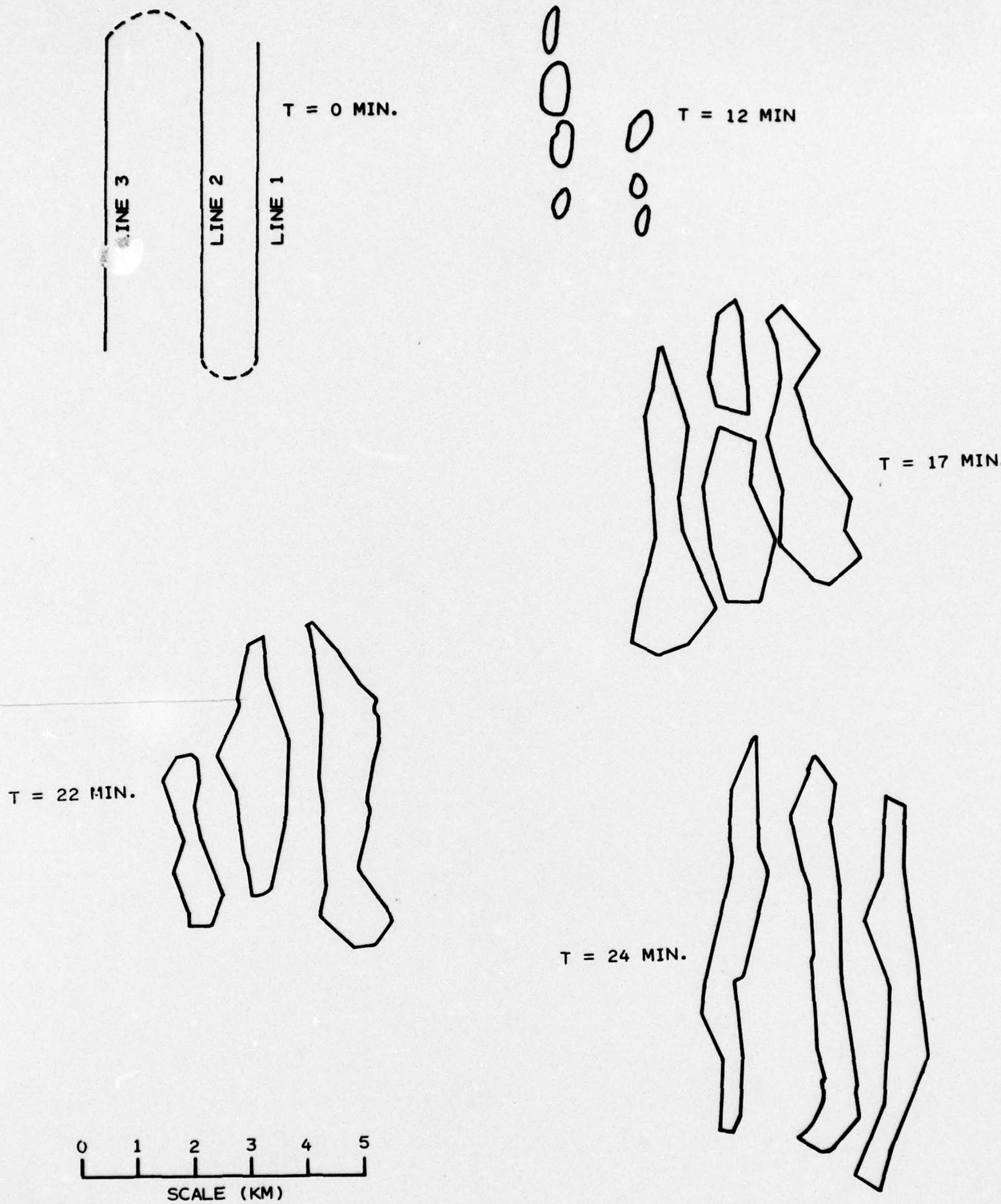

Figure D-6. Raster test, March 6 AM.